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The digital sustainable development of small Italian municipalities: the blockchain waste management case study

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List of Abbreviations and Terms

PAYT - Pay as You Throw

RENTRI - Registro Elettronico sulla Tracciabilità dei Rifiuti

FIR - Formulario Identificazione Rifiuti

SOPA - Sustainable Operations Process Analysis

BPS - Business Process Simulation

LCA - Life Cycle Assessment

ENRD - European Network for Rural Development

CBECI - Cambridge Bitcoin Electricity Consumption Index

CGIAR - Consultative Group on International Agricultural Research

CCAFS - Climate Change, Agriculture, and Food Security

NAI - Strategia Nazionale per le Aree Interne

ISPRA - Istituto Superiore per la Protezione e la Ricerca Ambientale

ANCI - Associazione Nazionale Comuni Italiani

MIMIT - Ministero delle Imprese e del Made in Italy

ARERA - Autorità di Regolazione per Energia Reti e Ambiente

MASE - Ministero della Transizione Ecologica e della Sicurezza Energetica

MiTE - Ministero della Transizione Ecologica

Chapter 1. Introduction and Overview of the Study

This research study addresses the crucial issue of the impact of waste management practices on the sustainable development of small villages in the Italian rural areas.

Even though the interest in sustainable rural development has only recently gained traction in managerial literature (Visvizi & Lytras, 2018), studies show that rural solid waste (RSW) represents a significant source of environmental pollution, and its effective management is crucial for the health of rural residents (Sun et al., 2024; Patwa et al., 2020). Furthermore, the waste management sites localized in rural areas cannot work independently: the waste management process involves the transportation of waste from one site to another, it is a long cycle that involves several stakeholders (Mihai, 2017; Salvia, 2021; ISPRA, 2024).

While previously the sustainable transformation of rural communities was predominantly explored in environmental studies, sociology, and agriculture (Visvizi & Lytras, 2018), the interest in rural waste management has surged following the introduction of European policy frameworks such as the European Union's Cohesion Policy and Common Agricultural Policy. These frameworks have spurred the development and implementation of theoretical and technological approaches to support rural sustainability.

Furthermore, addressing the rural areas aligns with the aim of implementing sustainable practices in the local communities, which the United Nations Sustainable Development Goals identified as the starting point of global sustainable practices (Joint SDG Fund, 2024)[1]. Achieving the Sustainable Development Goals (SDGs) by 2030 is a complex and pressing challenge, as nations worldwide seek to mitigate the detrimental effects of human activities on the environment, society, and the economy (Klessascheck et al., 2025). Starting at a local level is a way of translating high-level commitments into actionable steps. Specifically, Goal 11, "Sustainable Cities and Human Settlements," (SDGs)

[1] The concept of *localization* is further developed by the United Nations. Localizing the Sustainable Development Goals is the strategy that aims to recognize and address the specific needs of a community.

focuses on urban development while emphasizing the need to transform local communities to achieve broader sustainability objectives.

It is also proven that the traditional urban-rural dichotomy no longer supports a sustainable future (Akkoyunlu, 2015; Neil Khor et al., 2022). The OECD (2013) highlights that urban-rural interlinkages are the foundation of economies of scale in public services, and the production of public goods strongly depend on them. Consequently, advancing sustainable development requires a comprehensive strategy informed by a deep understanding of the needs and opportunities within rural areas.

The approach to sustainable development has changed over time: sustainable development, as a multidimensional and interdisciplinary concept, has been subject to extensive analysis and varying interpretations across different fields of study. For the purpose of this research, the definition established in the 1987 Brundtland Commission Report on Environment and Development is adopted. This report, issued by the World Commission on Environment and Development (WCED), emphasizes the necessity of a paradigm shift towards a sustainable development model that addresses global challenges such as economic inequality, climate change, technological disparities, and inadequate infrastructure (Zavratnik et al., 2018). The report defines sustainable development as "development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development, 1987, p. 43). This definition underscores the need for a balanced approach that simultaneously fosters economic growth, social inclusion, and environmental protection.

Furthermore, the Brundtland Report highlights the interconnectedness of sustainability-related challenges and stresses the importance of adopting holistic and integrated strategies to ensure long-term global well-being (Hajian et al., 2021). It advocates for policies that promote responsible resource management, equitable access to opportunities, and technological advancements that support sustainable progress. Understanding and operationalizing the Brundtland definition remains a cornerstone in contemporary discussions on sustainable development, guiding policymakers, businesses, and researchers in their pursuit of a more resilient and equitable future (Caiado et al., 2018).

Sustainable development is increasingly supported by the development of new digital technologies (Krajčo et al., 2019; Adamczyk, 2019; Popkova et al., 2022). The achievement of the sustainable development goals of the UN 2030 Agenda and the public policies for sustainable development and digitalization adopted in recent years go hand in hand: the latter become functional to the achievement of the former (Mondejar et al., 2021). Technologies such as IoT, artificial intelligence, or DLT technologies can support the implementation and monitoring of the Sustainable Development Goals of the 2030 Agenda (Asvis, March 2020; Feroz et al., 2021; Cricelli et al., 2021).

Therefore, new dimensions are added to the original Triple Bottom Line framework, which includes environmental, social, and economic governance sustainability: technical sustainability takes on an important role by representing the evolution of technological systems and their adaptability to the external environment, which is also constantly changing (Penzenstadler et al., 2013).

In the past decade, in the attempt to explore the potential of new technologies on sustainable development, researchers have increasingly focused on analysing a new and "smart world" in which technology facilitates sustainable resource consumption and improves overall living standards (Haider et al., 2018). Specifically, the adoption of new technologies to address the sustainability needs of small rural and peripheral communities has led to the emergence of the smart villages (SV) concept (Somwanshi et al., 2016).

Smart villages utilize digital technologies and innovative solutions to enhance quality of life, improve public services, and optimize resource management (Yannick et al., 2016; Jensen et al., 2024). They are distinguished by strong human and social capital, advanced digital connectivity, and a high capacity for innovation (Sutriadi et al., 2018; Subanda et al., 2023; Tosida et al., 2024). These communities typically consist of a village and its surrounding areas, forming a cohesive socio-economic unit (Slee et al., 2019). The smart village concept integrates various elements of urban life into smaller municipalities while preserving their rural identity, thereby contributing to national development (Slee et al., 2019; Anastasiou et al., 2021). Envisioned as digitally integrated rural ecosystems, Smart Villages offer a fertile ground for the deployment of innovative technologies for waste management practices (Somwanshi et al., 2016; Dutta et al., 2019; Mohanty et al., 2020).

The management of waste addresses an urgent sustainability challenge achieving net zero emissions in times where the global community is facing a climate emergency necessitating immediate action for several reasons. First, conventional waste management frameworks are becoming insufficient in managing the escalating quantities of waste, necessitating the development and implementation of advanced, systemic innovations (Kozel et al., 2018; Paul et al., 2019; Bułkowska et al., 2023). Additionally, studies show that the waste management disposal chain constitutes a highly intricate system, engaging a wide array of stakeholders (Lehtinen et al., 2019; Baralla et al., 2023). These typically include households and industrial actors; municipal authorities; third-party service providers responsible for waste collection and bin management; specialized facilities for sorting, disposal, and recycling; and manufacturers that reintroduce recycled materials into the market (Lehtinen et al., 2019; Baralla et al., 2023).

Furthermore, on the consumer side, the sector is impeded by complex behavioural patterns, frequent misclassification during waste sorting, infrastructural deficits, inefficiencies in recycling processes, and the evolving requirements of data governance and compliance with environmental regulations (Swami et al., 2011; Jiang, et al., 2023).

The peculiarities of rural areas add more factors to be considered when evaluating waste management systems are inherent to the peculiarities of rural areas. These areas are vast and sparsely populated, leading to non-centralized waste distribution (Sun et al., 2024). Unfortunately, even though the variety and volume of RSW is increasing annually, the recyclable value of RSW is still relatively low compared to municipal solid waste (MSW), complicating the establishment of a closed-loop waste supply chain in rural areas (Sun et al., 2024).

The issue of sustainable waste management is thoroughly analysed in the following chapters focusing on the Italian case. The most recent data on waste management practices identifies a traceability issue where waste is often collected and transported to other regions or countries for processing with a lack of assurance on the correctness of the data transmitted from one waste management plant to the other[2](Ispra, 2023). This is an issue for the sustainable development of these areas rich in natural resources and often growing to become valuable touristic spots.

Accurate monitoring and documentation of waste collection data are essential not only for regulatory compliance, but also for generating actionable insights that may inform policy development and help mitigate environmentally harmful disposal practices such as landfilling and incineration (Hannan et al., 2015). Nonetheless, the process of waste tracking and ownership attribution is inherently complex (Pongracz et al., 2024). Contributing factors include material fragmentation, legislative frameworks such as extended producer responsibility (EPR), which obligate producers to manage post-consumer waste, and the loss of ownership due to illegal dumping or littering (Pongracz et al., 2024).

Current tracking mechanisms are often insufficient, indicating the need for more robust and practical solutions to effectively monitor waste flows and stakeholder responsibilities (Steenmans et al., 2020; Strzelecka et al., 2024). In fact, although several issues with RSW management have been identified in literature and partly tackled by Global[3], European and National policies[4], due to the lack of proper data collection and data sharing systems, rural waste management is still scarcely debated in the academic literature, or at least less than SWM in urban areas (Mihai, 2018).

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[2] For a complete analysis of the waste traceability issue see Chapter 3.

[3] The Sustainable Development Goals on Target 11.6 aims at reducing the adverse per capita environmental impact of cities, including by paying special attention to air quality and municipal and other waste management. For the complete overview on the SDG agenda linked to waste management, see Chapter 3.

[4] The National Waste Management Plan 2030 (PNGR 2030) establishes the national strategy on the prevention and management of waste and the guiding rules that ensure its coherence with other plans and specific instruments aimed at contributing to decarbonization in the context of the necessary transition to a circular economy. However there are several Europan policies to be considered: Waste Framework Directive (2008/98/EC, amended by 2018/851); Landfill Directive (1999/31/EC); Packaging and Packaging Waste Directive (94/62/EC); Circular Economy Action Plan (2020); Plastics Strategy (2018); Eco-Design and Extended Producer Responsibility (EPR); Waste Electrical and Electronic Equipment Directive (WEEE Directive, 2012/19/EU); Batteries Directive (2006/66/EC).

Specifically, few studies have been developed on the implementation of blockchain technology to waste management in smart villages (Kaur et al., 2022; Gupta et al., 2021; Zhang et al., 2019). Blockchain waste management might have the potential to revolutionize waste management practices and foster circular economy principles (Adami et al., 2021; Castiglione et al., 2023; Aiguobarueghian et al., 2024)[5]. Due to the transparency and immutability features, blockchain can be used to track the amount of waste shipped, received, and recycled at the recycling plant, the credentials of the waste handler and their actions, and the storage location of waste when it is segregated sorted and recycled or disposed of (Gopalakrishnan, 2019). Based on the immutable record of data and transactions, the blockchain can verify and identify any missing waste by comparing the weight of received and shipped waste (Laouar et al., 2019).

Despite growing interest in blockchain applications, the existing literature remains largely focused on smart cities, offering limited attention to rural contexts and lacking empirical evidence of blockchain's positive impact on waste management in these areas. Given this gap, and the tendency to overlook the specific challenges and opportunities in rural settings, this research seeks to contribute to the emerging discourse on blockchain-enabled waste management in rural areas, particularly within the framework of smart villages, by building on the conceptual foundations previously outlined.

1.2 Research Objectives and key Research Questions

In order to respond to sustainable development issues and unanswered questions on sustainable waste management in rural areas, this study explores the potential impact of the innovation of waste management processes through blockchain technology.

As stated, blockchain technology is one of the technologies implemented in the smart village concept (Kuar et al., 2022). It represents a revolutionary shift in how data is managed and shared across

[5] For a comprehensive literature review of blockchain waste management see Chapter 2.

various sectors, it facilitates decentralized, secure, and transparent transactions (Olanrewaju et al., 2024; Esiri et al., 2024), it can enhance transparency by providing a secure and immutable record of waste transactions (Olanrewaju et al., 2024; Iwuanyanwu et al., 2024). These features enable stakeholders to track the movement of waste from its origin to its disposal or recycling, ensuring that it is handled in compliance with regulations. Therefore, it can be stated that blockchain can improve accountability in waste management by allowing all parties involved, including waste generators, collectors, transporters, and processors to have access to the same information (Abdul-Azeez et al., 2024). Additionally, it can streamline reporting and compliance by providing a reliable and tamper-proof record of waste management activities, making it easier for organizations to meet regulatory requirements and demonstrate their commitment to sustainability (Onukwulu et al., 2024; Adeusi et al., 2024).

Although the benefits of this technology are becoming increasingly apparent in waste management realm of studies, some questions remain still unanswered. Blockchain might be a true disruptive social innovation, but some wonder if it is another affectation of incremental technology with limited strategic significance for sustainable supply chains (Kouhizadeh et al., 2018). Furthermore, the benefits of this technology largely depend on the understanding of the financial burden and potential barriers to its adoption across these settings (Zhang et al., 2025).

Implementing new features through the blockchain is also suggested to make additional services more efficient in the waste management processes. For example, tracking or blockchain-based management of the sales of sorted waste boosts the application of the principles related to a circular and sustainable economy (Castiglione et al., 2023). Although blockchain-related technologies have been reported to be employed in small municipalities, it needs further investigation and assessment on whether similar applications with relatively low costs should be extended in rural areas (Jiang et al., 2023).

This study seeks to contribute to this nascent field by addressing several critical and previously unexplored questions:

- *RQ1:* To what extent can blockchain technology be theoretically and empirically validated as an effective tool for advancing sustainable waste management?
- *RQ2:* How and in which part of the waste management process design can blockchain-enabled features, such as tracking and transaction transparency, enhance efficiency and traceability?
- *RQ3:* What financial, infrastructural, or educational barriers hinder equitable adoption of blockchain technologies in marginalized or resource-constrained communities?
- *RQ4:* What are the environmental impacts of blockchain adoption in rural areas?

In order to answer the emerged research questions the following steps have been taken.

First, chapter 2. Has been dedicated to exploring the existing literature regarding smart villages defining the best practices and presenting the existing projects under the smart village initiative realm. Initially motivated by the aim of contributing to managerial practices in RSW management, the conceptual framework ultimately developed into a multidimensional analysis spanning three interrelated domains: (i) digital sustainable development, (ii) smart village initiatives, and (iii) modelling of waste management processes with an integrative approach.

The chapter specifically addresses the main characteristics that define the requirements and characteristics of the digital sustainable development in a smart village, the specific areas where digital sustainable development can be defined and the tools that have been studied so far. The outcome of chapter 2.1. is a conceptual framework of digital sustainable development in smart villages that showcases one of the potential areas where a smart village might benefit from technology: waste management. Blockchain waste management has been identified as an option to prevent traceability issues and therefore the pollution of the natural areas surrounding the villages areas. Subsequently, chapter 2.2. following the conclusions of the previous literature review further explores literature concerning blockchain waste management. The main goal of this section is to outline the main topics, challenges and opportunities retrieved in literature in support or against the blockchain waste management solution identifying the potential gaps in the research domain. The conclusion is that waste management is found to be compatible with technologies such as blockchain for several reasons. First, blockchain enables transparency, traceability, and accountability across the entire waste lifecycle from generation to final disposal; its immutable and decentralized ledger ensures data integrity, reducing the risks of fraud and manipulation in reporting, especially in documentation-heavy processes such as recycling and waste collection.

Second, blockchain enhances efficiency and coordination among multiple stakeholders, including municipalities, waste collectors, recyclers, and citizens. By enabling secure and real-time data sharing, blockchain facilitates smoother operations and faster decision-making, which are essential for smart waste management systems.

Third, it supports incentive-based models that encourage proper waste disposal behavior. Reward systems using tokens or social cryptocurrencies have shown promise in motivating individuals and communities to sort and recycle waste correctly, aligning with circular economy principles.

Fourth, blockchain proves particularly valuable when integrated with IoT devices and digital infrastructure (e.g., smart bins and sensors). This integration allows for real-time monitoring of waste levels and efficient route planning for collection, which reduces costs and environmental impact.

Fifth, blockchain aligns with the goals of sustainable development and circular economy models. It supports governance characteristics such as participation, responsiveness, and effectiveness, while enabling PAs to structure more sustainable, resilient service delivery models.

However, unanswered questions remain. Apart from the technical limitations, the lack of regulatory frameworks, user training needs, digital infrastructure gaps (especially in rural areas), and institutional resistance to innovation, a design and impact evaluation of blockchain waste management in rural areas is still missing, which leaves space to the creation of conceptual frameworks not considering the empirical or potential impact of the technology.

Chapter 3. has been designed to understand the current state of waste management in Italian villages and, even more specifically, its rural areas. The historical context of waste management rules and laws has been outlined and the link with European policies has been explored. Furthermore, successful case studies of waste management projects have been outlined.

The conclusions of the chapter bring several questions. Effective waste management in rural areas faces persistent challenges due to dispersed populations, limited infrastructure, and weaker institutional capacity. While small municipalities have implemented useful practices like PAYT schemes and home composting, these efforts often lack coordination and traceability. Introducing digital traceability tools, such as those supported by systems like RENTRI, can enhance transparency, prevent illegal dumping, and improve data-driven decision-making.

However, the Italian traceability system is not interoperable with European systems, which means that cross-border waste shipments remain outside its scope and lack traceability. Additionally, there is a lack of comprehensive studies assessing the environmental and economic impacts of such systems in rural settings. To meet circular economy goals and EU directives, investing in scalable, user-friendly traceability infrastructure is essential. Future research should focus on evaluating these tools' systemic benefits using multi-criteria methods that consider environmental, economic, and social dimensions to guide effective policy decisions.

The methodological approach has been outlined in Chapter 4. Developing on a pragmatic philosophical stance and an abductive approach to research, the study applies a mixed method study using SOPA methodology based on a single case study. The data analysis methodology adopted in this research is grounded in the SOPA framework, a structured three-step approach designed to assess the environmental impacts of business processes and support their sustainability-oriented redesign.

Chapter 5. presents a case study analysis of a waste management facility in the provence of Rome.

The chapter explores the implementation of blockchain technology in waste management through an in-depth case study set in a facility located within a protected natural area in the Roman Provence. Building on the methodological framework, it begins with the collection and analysis of data from the facility, leading to the development of a detailed representation of the existing waste management process. This process is examined to identify key transactions and data storage practices. Using these insights, a blockchain-based model is proposed and evaluated according to the SOPA methodology, highlighting the potential improvements in transparency, traceability, and efficiency. The chapter concludes with a qualitative assessment of the environmental implications of introducing blockchain, aiming to offer meaningful contributions to both theoretical discussions and practical advancements in sustainable waste management.

Finally, Chapter 6. Draws the conclusions, considerations and presents the limitations of the study.

Chapter 2. Literature Review

This chapter discusses the conceptual background to the present study. Relevant literature is presented, and the research approach is proposed. Section 2.1 is dedicated to the definition of digital sustainable development in Smart Villages through the analysis of international case studies. Section 2.2 summarises the most important research on blockchain waste management. 2.3. Presents the proposed research and the research design in the light of the theory discussed in this chapter.

2.1 Smart Villages: A Global Multiple Case Study Analysis

Although research has shown that the traditional dichotomized or binary relationship between urban and rural human settlements no longer supports a sustainable future (Akkoyunlu et al., 2015; Neil Khor et al., 2022), the interest in the sustainable development of rural areas has only recently grown in managerial studies (Visvizi & Lytras, 2018). A major positive impact on the development of this field of study is identifiable with the introduction of new European policy frameworks such as the

European Union's Cohesion Policy[6] and Common Agricultural Policy (CAP)[7]. Through these policies several theoretical and technological frameworks have been proposed and implemented to support rural areas in their sustainable development recognizing that the investments in environmental protection, rural infrastructure and rural health and education are critical to sustainable rural development and can enhance national well-being (Transforming our world: the 2030 Agenda for Sustainable Development). These policies are in support of the European Vision and Action Plan which identifies four areas of action to enable "stronger, connected, resilient and prosperous"[8] rural areas.

To understand the needs and the importance of rural areas, one of the key concepts to explore preliminarily is sustainable development: a multidimensional and interdisciplinary concept, which has been subject to extensive analysis and varying interpretations across different fields of study. For the purposes of this research, the definition established in the 1987 Brundtland Commission Report on Environment and Development will be adopted.[9] The report, issued by the World Commission on Environment and Development (WCED), emphasizes the necessity of a paradigm shift towards a

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[6] The European Cohesion Policy plays a central role in advancing several EU policy objectives, including education, employment, energy, environmental sustainability, the single market, and research and innovation. Investments made through Cohesion Policy projects across EU regions and cities directly contribute to broader Commission priorities, notably the European Green Deal, A Europe fit for the digital age, and an economy that works for the people. The policy is rooted in the objective of Economic, Social, and Territorial Cohesion, as enshrined in Articles 174-178 of the Treaty on the Functioning of the European Union (TFEU). Notably, Article 174 stipulates the Union's aim to reduce regional disparities and support the development of less-favoured regions, including rural areas, zones in industrial transition, and territories facing severe or permanent natural or demographic challenges.

[7] The Common Agricultural Policy (CAP), established in 1962, serves as a strategic partnership between agriculture and society. It supports EU farmers' incomes and productivity, encourages environmental sustainability, fosters rural development, and sustains the vitality of rural economies. The CAP 2023-2027, effective from 1 January 2023, builds on this legacy by providing tailored support to farmers and rural stakeholders through instruments such as national and regional rural development programs, market regulation, and income support mechanisms.

[8] The strategy focuses on empowering rural communities, improving access to services, facilitating social innovation while improving connectivity both in terms of transport and digital access. Additionally, the goal s to preserve natural resources and greening farming activities to encounter climate change while ensuring social resilience. Finally, the diversification of economic activities comprehends the value added of farming and agri-food activities and agri-tourism.

[9] World Commission on Environment and Development, 1987, p. 43.

sustainable development model that addresses global challenges such as economic inequality, climate change, technological disparities, and inadequate infrastructure (Zavratnik et al., 2018). The report defines sustainable development as "development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs" (Brundtland, 1987, p. 43). This definition underscores the need for a balanced approach that simultaneously fosters economic growth, social inclusion, and environmental protection.

Furthermore, the Brundtland Report highlights the interconnectedness of sustainability-related challenges and stresses the importance of adopting holistic and integrated strategies to ensure long-term global well-being (Hajian et al., 2021). It advocates for policies that promote responsible resource management, equitable access to opportunities, and technological advancements that support sustainable progress.

Understanding and operationalizing the Brundtland definition remains a cornerstone in contemporary discussions on sustainable development, guiding policymakers, businesses, and researchers in their pursuit of a more resilient and equitable future (Hariram et al., 2023).

To ensure the practical application and measurable outcomes of sustainable development, the United Nations introduced the 2030 Agenda with its 17 SDGs. According to this framework, sustainability must begin at the local level. Goal 11, "Sustainable Cities and Human Settlements," focuses on urban development while emphasizing the need to transform local communities to achieve broader sustainability objectives. Whereas sustainability initially referred exclusively to the so-called Triple Bottom Line introduced by Elkington in the 1990s (considering environmental, social and economic sustainability)[10], today sustainable digital development is becoming an increasingly important topic for monitoring the impact of technologies on a social, environmental and economic level (Cricelli et al. 2021). Innovation and digitalization are powerful tools for the realization of a better society, as

[10] For further knowledge on the Triple Bottom Line: Elkington, J., & Rowlands, I. H. (1999). Cannibals with forks: The triple bottom line of 21st century business. *Alternatives Journal*, *25*(4), 42.

they transform people's habits and ways of thinking and, consequently, the environment, society, culture and the economy (Sparviero, 2021).

Even more specifically, a long-term vision for the rural areas has been outlined by the European Commission (EC Report, 2021), aiming to build on the emerging opportunities of the EU's green and digital transitions and on the lessons learnt from the COVID19 pandemic, achieving a balanced and sustainable territorial development stimulating economic growth ("Long-term Vision for rural areas", EC, 2021).

Epifani uses the term "digital sustainability", thus describing the means of creating scalable socio-ecological value for all companies embarking on a digital innovation journey (Epifani, 2021). In his book entitled "Digital sustainability: why sustainability cannot do without digital transformation (in Italian)", he describes digitisation as *"an activity aimed at optimising processes through the use of automation and re-engineering".* Thinking and planning, in terms of digital sustainability means wisely using digital technologies to enhance the universal values of sustainability (equality, harmony, self-determination) to improve the quality-of-life of individuals, having a positive impact on society and the economy, all while respecting and protecting the environment (Sparviero, 2021).

Digital sustainability is defined as a "cluster of values" which, when applied to new technologies, contribute to a sustainable future. Sustainable digital development follows a set of instrumental values of creating and adopting technologies in the pursuit of sustainability (Sparviero, 2021).

Authors such as Penzenstadler and Femmer (2013) consider five dimensions of sustainability: individual, social, economic, environmental and technical. The latter considers the evolution of technological systems and their adaptability to the external environment, which is also constantly changing (Penzenstadler et al., 2013). Technical sustainability is closely related to environmental sustainability, but also to economic sustainability, considering the use of innovative technologies to reduce the consumption of water resources, the amount of waste and the use of energy (Cricelli et al. 2021).

New technologies have been adopted to meet the sustainable development needs of small rural and peripheral centres, leading to the development of the concept of smart villages (SV): local communities that make use of digital technologies and innovations on a daily basis, thereby improving the quality of life and the standard of public services and also ensuring a more efficient use of resources (Cork 2.0 Declaration 2016 "A better life in rural areas"). Within the context of Smart Villages, the notion of digital sustainable development takes on particular significance. Smart Villages are characterized by the integration of digital technologies into rural areas to enhance the overall quality of life, economic vitality, and environmental sustainability (Gerli et al., 2021; García Fernández and Peek, 2023).

Smart villages are used as a descriptor for communities which have both strong human and social capital and good digital connectivity and whose capacity to deliver innovative solutions is high. Therefore, the spatial scale is usually a physical community, i.e. the village and its hinterland (Slee, 2019; Gorain, 2021; Renukappa et al., 2024).

The smart village concept introduces many of the aspects of life in urban centres into small municipalities while preserving the characteristics of typical rural areas and ensuring their development at a national level. The aim is to provide a sustainable and fulfilling lifestyle to the inhabitants who might refrain from abandoning their municipality of residence (Adesipo et al., 2021). The concept of Smart Villages (SVs) gained significant attention following the signing of the Cork 2.0 Declaration in 2016, which served as a defining moment in the development of this concept. During this pivotal event, the notion of Smart Villages was officially defined as rural communities that leverage innovative solutions across various sectors of economic activity to improve their socio-economic well-being, utilizing local assets and seizing new opportunities. While the role of Information and Communication Technology (ICT) in supporting the growth and development of Smart Villages is widely recognized, some scholars argue against a solely technocentric approach (Vizvizi & Lytras, 2018). They emphasize that human capital, social cohesion, and community engagement are just as essential to the success of Smart Villages as technological infrastructure. This perspective contrasts with the typical approach in Smart Cities (SCs) literature, where ICT is often regarded as the central driver of innovation, smartness, and overall progress (ENRD, 2018).

Over time, a range of scholars and institutions have proposed alternative definitions of Smart Villages, each highlighting different dimensions of the concept. The European Network for Rural Development (ENRD) offers a definition that underscores the importance of local resources and opportunities. According to the ENRD, Smart Villages are "rural areas and communities that build on their existing strengths and assets while also developing new opportunities" (2018, p. 7). This definition emphasizes the importance of local community resources in fostering resilience and growth. In parallel, the Consultative Group on International Agricultural Research (CGIAR) introduced the idea of "Climate-smart villages," which reflects an integrated approach to addressing climate change and food security. In this framework, the Climate Change, Agriculture, and Food Security (CCAFS) program works alongside rural communities and stakeholders to test and implement agricultural practices that are both sustainable and resilient to climate change. Furthermore, the IEEE Smart Village presents a distinct perspective, focusing on providing comprehensive solutions to communities affected by energy poverty. Their model integrates renewable energy technologies, community-based education, and entrepreneurial opportunities, all aimed at driving sustainable development in underserved rural areas. Interestingly, none of these definitions place heavy emphasis on technology as a primary driver. In contrast, Zhang (2020) identifies access to ICT and its application for sustainable development as a critical differentiating factor that sets Smart Villages apart from other development models.

In European conditions, smart is usually connected with knowledge and innovations, which tend to concentrate in cities (Naldi et al., 2015). Smart Villages strategies can be formulated at the level of village settlements, municipalities, groups of municipalities or other small-scale discrete territorial units (e.g. islands or groups of islands). As a rule, the spatial scale of a Smart Village Strategy will start small and grow through cooperation with other areas (ENRD, 2019).

The local communities in rural areas are considered particularly relevant for the sustainable development goals defined by the United Nations in 2015, that aim at reducing the negative impact of human activities by 2030. Specifically, Goal 11 of the 2030 Agenda called “Sustainable cities and human settlements” focuses on the development of urban areas suggests that, to achieve the global sustainability goals, it is necessary to start with the transformation of individual local communities.

European demographic databases show that these communities are particularly significant in Europe. According to the OECD definition, most of Europe is classified as rural (Predominantly Rural - PR - or Intermediate Rural - IR). Only 26% of NUTS3 regions appear to be urban (Predominantly Urban - PU), whereas 40% is classified as PR and 34% as IR (Bertolini et al., 2008). These are territories characterised by rapid and relentless depopulation due to the lack of basic services.

Even though depopulation is considered a symptom of rural decline rather than a cause, there is no doubt that it is one of the main factors driving the smart villages agenda (Hess et al., 2018).

The problem of depopulation of rural areas has several facets worldwide: it displays diverse dynamics, and country/region-specific factors contribute to its evolution. Nonetheless, research on smart villages is not solely geared toward the issue and implications of decreasing populations in villages. According to the OECD (2013), economies of scale in public services and the production of public goods depend on successful rural-urban interlinkages. To move towards sustainable development goals, the present complex geographical pattern requires a common strategy based on an in-depth knowledge of the needs and opportunities of the rural areas.

There is a need for research focusing on the declining of the quality of life and wellbeing, the emergence of externalities in the form of strain on cultural heritage and the pollution of the environment (Visvizi & Lytras, 2018). Sustainability starts with the needs of individuals (Cavagnaro et al., 2022), and so it is grounded in individual values, before social ones. Equality, harmony and self-determination are some universal values when approaching sustainability issues.

Nonetheless, the economic, social and environmental goals of sustainability need to be considered simultaneously and linked to the level of digital literacy of individuals, which encompasses a set of skills that is defined by UNESCO (2008) as “the ability to access, manage, understand, integrate, communicate, evaluate and create information safely and appropriately through digital devices and networked technologies for participation in economic and social life. It includes competencies that are variously referred to as computer literacy, ICT literacy, information literacy, and media literacy” (UNESCO, 2018, p. 21). Digital is a vital component of the SDGs the 4.4 target aims at increasing the share of individuals with relevant technical and vocational skills for qualified jobs.

Interventions and policies concerned with sustainable digital development can vary and yet converge toward the same ultimate goals of sustainability. Furthermore, promoting digital sustainability means putting a way to tackle the negative impact related to the advent of digital technologies at the center of policymakers and private stakeholders’ agenda. To understand the role of smart villages in digital sustainable development, the following paragraphs explore existing examples adopting a multiple case study approach (Yin, 2003). By leveraging secondary data, the study provides a comprehensive view of the historical and contemporary developments in Smart Village initiatives. The combination of various data sources enables a richer understanding of digital sustainable development in rural communities and the challenges they face as they transition toward greater sustainability.

Technology can contribute to the sustainable transformation of rural communities.

2.1.1 Case study selection

In case study research, the selection of cases is a crucial step that directly influences the relevance and depth of the findings. A case is typically chosen for its critical importance, uniqueness, revelatory characteristics, or exemplary nature, as these factors provide an appropriate context for addressing the specific research questions under investigation (Yin, 2003). The rationale behind selecting such cases is to capture a wide array of information that can illuminate the underlying dynamics of the research topic. Eisenhardt (1989) further emphasizes the value of case studies in theory development, asserting that they can serve as a foundational starting point for building new theoretical frameworks. According to her, a cross-case analysis that includes 4 to 10 distinct case studies can provide a robust basis for drawing analytical generalizations, especially when these cases are carefully chosen to reflect a variety of conditions and contexts.

In this study, six smart village (SV) projects were selected. These were chosen based on the specific criteria outlined in Table 1. These criteria were formulated to align with the primary objective of the research, which was to observe both the similarities and differences across geographically dispersed case studies. The aim of the study is to gain a comprehensive understanding of the diversity of approaches to digital sustainability practices globally, by comparing projects from four distinct geographical areas. This comparative analysis is essential for identifying overarching trends, as well as region-specific variations, in the implementation of digital sustainability initiatives. To ensure the reliability and credibility of the data, the study focused exclusively on institutional smart village projects. This decision was guided by the necessity of obtaining an accountable and scientifically rigorous dataset, which would be representative of well-established and formally recognized projects. In doing so official websites, government publications, and related academic research papers were consulted to identify and select the relevant cases. By narrowing the scope to institutional projects and utilizing credible sources of information, the robustness of the dataset and its suitability for the purpose of this study was ensured. This methodological approach allowed for a clear and coherent examination of current global practices in digital sustainability, providing insights that could inform future research and policy development in this important area.

Table 1 - Case selection criteria

Criteria	**Objective**
Geographical area diversity	The study aims at comparing practices from culturally and economically diverse areas by analyzing SV projects from each continent.
Digital-based projects	The aim is to synthetize sustainable and digital practices in SVs.
Institutional projects	In order to collect accountable data only SV projects carried out by institutions or with institutional funding were selected.

Source: Authors

The chosen projects are part of three international initiatives: the ENRD, IEEE Smart Village and CGIAR. The projects are based in the four continents: Africa, Asia, Europe and South America.

2.1.2 Findings

The case studies presented in this report offer a comprehensive analysis of various development initiatives implemented across six municipalities, each representing a different continent, as detailed in the methodological section and summarized in Table 1. These municipalities were strategically chosen to encompass a diverse range of geographical, cultural, and socio-economic contexts, ensuring a broad understanding of global development challenges and solutions. Each case study provides a detailed overview of the specific conditions prevailing in the municipality, including key demographic factors such as population size, geographical area, and infrastructure. Additionally, the case studies highlight the principal obstacles hindering growth in these regions, including economic, social, environmental, and political challenges that undermine efforts towards sustainable development.

In parallel with contextual insights, the case studies also present tailored solutions aimed at addressing these challenges, focusing on how economic and social activities can be leveraged to overcome regional barriers. These proposed solutions are aligned with the broader goals of enhancing economic stability, improving the quality of life for local inhabitants, and ensuring long-term sustainability. Each case study outlines the core objectives of the respective development initiatives, offering clarity on the specific aims of the projects. Moreover, the case studies describe the innovative technologies being utilized to promote sustainability, such as renewable energy solutions, waste management systems, and smart city technologies, all of which contribute to a more sustainable and resilient future for these municipalities.

The action plans featured in the case studies emphasize the concrete steps necessary for the successful execution of these initiatives. These plans detail the resources, financial investments, and human capital required to bring these projects to life, as well as the roles of key stakeholders, including local governments, community organizations, and private-sector partners, all of whom are essential to the successful implementation of the initiatives. The case studies adopt a structured and accessible descriptive approach, providing a thorough understanding of the strategies employed to address development challenges across the municipalities.

Case Study 1: Vaishali District, Bihar, India

The Vaishali District case study explores one of the most populous districts in India, encompassing a total area of 2,036 square kilometers and a population of approximately 3.5 million, according to the 2011 census. The district faces extreme climatic conditions, with hot summers and relatively cold winters, and its economy is largely dependent on agriculture. Given the growing concerns over the impact of climate change on agriculture, food security, and livelihoods, a collaborative effort was launched to enhance climate resilience in agriculture through the CGIAR-IFFCO Foundation Participatory Action Research project. This initiative aimed to promote climate-resilient farming through the combined efforts of implementing agencies, local community organizations, and farmers. Key interventions included the development of farmer organizations, gender-sensitive training programs, weather-based agro-advisory services using media and ICT, index-based insurance, the screening of crop varieties, and eco-friendly practices related to nutrient and water management. A particularly noteworthy intervention involved the integration of mung beans into crop rotation systems, which proved to be more sustainable and productive compared to traditional farming practices in the area.

Case Study 2: Wakiso District, Uganda

The second case study focuses on Wakiso District, Uganda's second most populous district, with over two million inhabitants. Wakiso faces significant challenges due to rapid urban migration, poverty, and underdeveloped infrastructure. In response, the Africa Development Promise (ADP) organization has worked to empower women farmers, helping them transition from subsistence farming to market-oriented agriculture. ADP created a network of cooperatives and training centers, focusing on enhancing management, networking, and technology skills among local women farmers. The initiative also provided funding for the acquisition of electric sewing machines and computers to support the establishment of cooperative businesses and digital literacy programs for women and youth. These efforts are aimed at boosting women's economic independence while fostering digital inclusion within the community.

Case Study 3: Wiązownica-Kolonia, Poland

In the village of Wiązownica-Kolonia in Poland, which has witnessed a gradual population decline of over 100 residents in the past decade, a series of projects were implemented to address rural depopulation and enhance local quality of life. The village's projects were designed to support its digital transformation, improve public safety, and encourage local engagement. Funded by a mix of government and private grants, the initiatives included the establishment of an information and consultation blog, computer literacy training for residents, and the installation of a video surveillance system for increased public safety. Additionally, a mural was created on an abandoned dairy building to revitalize public spaces and foster community identity. These efforts highlight the role of local organizations in mobilizing residents to take part in development projects that combine digital tools and social initiatives to counteract depopulation.

Case Study 4: Olopa, Guatemala

The final case study examines the Climate-Smart Village (CSV) approach implemented in Olopa, Guatemala, aimed at addressing the negative impacts of climate change on agricultural activities. The region, primarily dependent on coffee, corn, and bean production, faces significant vulnerability due to unpredictable weather patterns. To address this, the CSV model encouraged farmers to adopt climate-resilient farming practices, including water conservation techniques, soil erosion prevention methods, and the use of drought-resistant crops. Furthermore, the introduction of Participatory Integrated Climate Services for Agriculture (PICSA) methodologies in 2019 helped empower local leaders and farming communities by providing them with seasonal climate forecasts and practical recommendations for crop management. This initiative has significantly enhanced the resilience of local farmers to climate variability and extreme weather events, while also promoting sustainable agricultural practices.

Aligned with the European Network for Rural Development (ENRD) classification, the presented Smart Village (SV) projects fall within the categories of Excluded (A, B, D) and Connected (C) Villages. Despite the differing socio-economic and geographical contexts, all of the case studies share a common goal: to bridge the digital divide and promote digital sustainability in rural areas. Digital literacy plays a critical role in this process, serving as the foundation for broader socio-economic development and the empowerment of local populations. The case studies confirm that digital skills are crucial for overcoming barriers such as rural depopulation, poverty, and limited access to services, ensuring that communities are better equipped to navigate the digital age.

Digital sustainability, as demonstrated in the case studies, is underpinned by three core principles: equality, harmony, and self-determination. The principle of equality emphasizes ensuring that all individuals, regardless of background, have access to digital tools and the opportunity to develop relevant skills. The principle of harmony focuses on aligning digital transformation with local needs, ensuring that technological advancements do not overwhelm existing resources or disrupt social structures. Finally, self-determination highlights the importance of empowering communities to take control of their digital futures by equipping individuals with the skills and knowledge needed to independently navigate and utilize digital technologies.

Case Study 5: Subugueiro, Portugal

The village of Sabugueiro, perched at 1,150 meters in the Serra da Estrela mountains and known as the highest village in Portugal, became the site of an innovative pilot project designed to illustrate how the principles of smart villages can reshape the future of remote rural communities. With roughly 480 inhabitants living in a low-density, mountainous environment, Sabugueiro faced persistent challenges common to isolated regions, including limited mobility options, inefficient public services, constrained economic activity, aging infrastructure, and insufficient access to essential amenities. The smart village initiative, funded by the Vodafone Foundation and implemented in collaboration with the City Council of Seia, local civil society organizations, the Parish Council, the Local Health Center, and Águas do Zêzere e Côa, sought to overcome these structural barriers by leveraging fiber-optic connectivity as the foundation for a broad portfolio of digital and technological solutions. In line with European smart village strategies, the project emphasized community empowerment, environmental efficiency, public service modernization, and digital inclusion, turning Sabugueiro into a living laboratory for sustainable rural development. Through the deployment of intelligent public lighting systems, real-time energy monitoring tools for households, and adaptive building management technologies, the community achieved notable gains in energy efficiency. Mobility improvements, such as digital access to transportation schedules, shared mobility coordination, and optimized service routes helped reduce social isolation and environmental impact. Health services were strengthened through telemedicine platforms and remote diagnostic tools that particularly benefited elderly residents.

One of the most transformative dimensions of the project involved modernizing water and waste management, areas that traditionally present significant difficulties in sparsely populated rural settings. Smart meters and digital monitoring systems enabled early detection of leaks, improved water distribution planning, and supported more responsible household consumption. Waste management benefited from the introduction of sensor-based systems capable of tracking waste levels and optimizing collection schedules, significantly reducing unnecessary trips, fuel costs, and emissions. These innovations contributed not only to environmental protection but also to the financial sustainability of municipal services. By integrating circular economy principles, the project strengthened local awareness about waste reduction, recycling practices, and resource stewardship, positioning Sabugueiro as a model for environmentally responsible rural governance. The project's holistic approach shows that smart village strategies are most effective when they combine technological infrastructure with social engagement, local governance coordination, and environmental goals, offering a replicable roadmap for other rural areas seeking sustainable modernization.

Case Study 5: Košeca, Slovakia

Košeca, a village in the Trenčín Region of north-western Slovakia and a gateway to the Strážov mountain range of the Inner Western Carpathians, situated at 255 meters of altitude and covering nearly 19 km^2, benefits from strong transport connections by road and rail and lies just 2 km from the district town of Ilava, while also maintaining a vibrant social life through numerous associations, clubs, festivals, and community events. Building on this active community foundation, the municipality undertook a long-term, systematic effort to improve waste management, culminating in the introduction of an advanced smart data monitoring system designed to reduce residual waste, increase recycling rates, and financially reward households for environmentally responsible behavior. The system uses stickers with unique QR codes for recycling bags and RFID chips embedded in waste bins, which are scanned by refuse collectors using smart watches issued daily by the municipal office. These digital tools enable precise tracking of the volume and type of waste generated by each household and business, allowing the municipality to apply a sliding-scale system of waste-collection fees that incentivizes recycling: households that recycle less than 15% of their waste receive no fee reduction, while those exceeding a 90% recycling rate benefit from a reduction of up to 55%. Košeca collects a wide range of materials, including plastic, metal, paper, glass, and tetra packs, and also operates its own composting site where residents can bring green waste, thus further promoting sustainable practices. The implementation of the digital tracing system was supported through training for refuse collection teams on using the technology, as well as capacity-building for municipal staff to interpret and utilize the collected data effectively. A strong information campaign, particularly focused on local schools, helped raise public awareness about the importance of waste sorting, recycling, and the long-term environmental benefits of responsible waste management. As a result, Košeca has significantly improved the quality and efficiency of its waste management services, making the village a more attractive place to live and work, reducing municipal waste-management costs, and freeing up resources that can be redirected toward other local services or used to lower local taxes. Beyond immediate environmental gains, the successful use of Internet of Things technology in Košeca demonstrates the broader potential for similar digital solutions to modernize additional municipal services, reinforcing the village's role as a forward-looking rural community that leverages technology to enhance quality of life and sustainability.

Final Considerations

This study has identified three significant outcomes based on the analysis of six case studies from different socio-economic and cultural contexts. Firstly, while there are variations in broadband access across global Smart Villages, digital innovation aimed at sustainability is the overarching goal in all projects. Secondly, the principles of equality, harmony, and self-determination were consistently applied across the initiatives, fostering inclusive, balanced, and empowering digital transformations. Lastly, the study highlights the need for more widespread dissemination of Smart Village projects to share the best practices and successes, which can be facilitated by larger initiatives such as CGIAR, IEEE Smart Village, and ENRD.

2.2 Blockchain Waste Management: Features and Application Challenges

In order to explore the possible implementation and impact of blockchain technology on waste management, the main features and application challenges are being analysed in the following paragraph. PAs are responsible for making the right strategic decisions that directly affect communities, yet only with accurate data, it is possible to design systems with the right number of vehicles, establish efficient routes, set targets, and track progress (Lakhouit, 2025). Studies show how blockchain technology is an opportunity to facilitate a variety of processes (Viriyasitavat et al. 2022), however, there are several conditional challenges that must be overcome to realize blockchain technology's full potential (Habib et al., 2022).

This systematic literature review explores the current research topics and challenges regarding blockchain adoption in waste management aiming at sharing future directions for Public Administration. The research has the aim to serve as an overview of the current state-of-art of the blockchain technology solution leading to the obtainment of the United Nations Sustainable Development Goals (SDGs). It highlights how blockchain technology applications in waste management have the potential of changing the current organizational patterns and facilitating the Public Administrations in assuring cleanliness and healthy environments for communities.

This systematic literature review makes several useful contributions. First, identifying the main research topics and research methods, it enables researchers to identify which areas are yet to be explored and, it shows those that have already been discussed by extent in literature. Second, the need for more in-depth research has emerged in order to have a full understanding of the situations in which blockchain technology is beneficial.

Among the public services that are impacting sustainable development, waste management plays a fundamental role. Nowadays resource production and waste generation have reached such proportions that lead to unprecedented environmental degradation, climate change, and pollution violating basic human rights and needs (Rakesh et al., 2021). The risk is that, by 2050, the world will generate 3.40 billion tons of waste annually (Silpa et al., World Bank Group, 2018). The World Bank describes waste management as the collection of solid waste from the point of generation to the point of treatment or disposal. Yet a more comprehensive definition of waste management in line with the sustainable development challenge states that waste management is the ability to deal with waste generated and eliminate its destructive effects on the environment, economy, human health, etc. (Ishtiaq et al., 2018). The importance of waste management in sustainable development is reinforced by the UN's Sustainable Development Goals, goal 11, i.e., "Sustainable Cities and Communities" in target 11.6 aims at reducing the adverse per-capita environmental impact of cities paying attention to municipal and other waste management by 2030 (The Global Goals).

To pursue sustainable development, PA should make strategic decisions that affect the daily health, productivity, and cleanliness of communities due to the global consumption patterns and waste management (Silpa et al., World Bank Group, 2018). The main challenge is linked to the expensiveness of urban waste management and the limited resources, the capacity of planning, contract management, and operational monitoring. Waste management operations must contend funding with other priorities for communities such as clean water, education, and healthcare when nearly 4 percent of the budgets in high-income countries are already dedicated to waste management - the budget rises to 20 percent in low-income countries. Only with accurate data, it is possible to design systems with the right number of vehicles, establish efficient routes, set targets, and track progress (Silpa et al., World Bank Group, 2018).

Innovations in public service delivery, empowered by ICT technologies, allowed many governments to improve the quality and affordability of public services, increase productivity and add value for each dollar spent. This resulted in more openness, greater transparency, higher productivity, better performance, and more sustainable services (Compendium of Innovative Practices in Public Governance and Administration for Sustainable Development, 2016). At the same time, good governance is not only affected by technology and innovation - it is also an enabler of technological development and innovation. It is shown how countries that have an open and transparent governance system have been able to promote better creativity, experimentation, learning, and innovation (Compendium of Innovative Practices in Public, Governance, and Administration for Sustainable Development).

Studies show how blockchain technology offers governments new means to assure transparency, prevent fraud and establish trust in the public sector (Rizal et al., 2018). Blockchain technology is a peer-to-peer distributed network that contains the complete record of transactional ledgers in an immutable and transparent manner (Chen et al., 2018, Shaik et al., 2021).

Between digitalization and sustainability, the concept of blockchain is defined as “a technology for sustainability transformation of the linear economic paradigm” (Centobelli et al., 2021, Bockel et al., 2021). In fact, blockchain can favor the adoption of circular practices thanks to a double integration that clearly identifies those responsible for the entire lifecycle of waste flows, with a reduction in management costs and control time (Centobelli et al., 2021, Krajnakova et al., 2019). However, blockchain adoption and use in the context of waste management is only partially explored in academic research.

This article aims to explore the current research topics and challenges regarding blockchain adoption in waste management and sharing future directions for public administration (PA). To do this, the authors have chosen to use a systematic literature review (Tranfield et al., 2003). This enables the identification of the main literature gaps and the future research fields that could still be developed. Nonetheless, the research might serve as an overview of the current state-of-art of blockchain technology solutions leading to the obtainment of the United Nations Sustainable Development Goals (SDGs).

To pursue this aim, the following research questions have been formulated:

RQ1: What are the main characteristics of literature regarding blockchain in waste management?

RQ2: What are the main applications of blockchain in waste management analysed by current literature?

RQ3: What are the challenges that the PA may face in introducing blockchain technology in waste management?

After reviewing the literature, the most analysed topics by scholars have been identified. Furthermore, the most-used methods to carry out this research and the geographical regions from which researchers have published (RQ1) have been identified. The main applications of blockchain technology have been outlined (RQ2), and the main challenges for the PA are identified (RQ3). The paper is structured as follows. Section 2 is dedicated to explaining the technological background of blockchain technology to fully represent its potential and the deserved attention in this research; section 3 is dedicated to explaining the methodological approach used to carry out this study; section 3.1 indicates the process used to select the articles and section 3.2 indicates the analytical framework applied. In section 4, the findings of the analysis are reported. This is followed by a discussion in section 5. In section 6, conclusions are drawn, and in section 7 future research directions are suggested, including the value and limitations of the study.

In order to fully disclose the importance of blockchain technology solutions, the article offers a brief overview of the topic.

2.2.1 Blockchain Technology

Blockchain is a decentralized network that uses Distributed Ledger Technology (DLT) to process data in a transparent, immutable, and secure manner. Shrivastava et al. have described blockchain technology as “an ongoing growing list of registrations of transactions that are divided into blocks”. Each block in the structure of the blockchain is made of a new set of transactions and all the transactions that occur in the network are recorded by the blockchain in a distributed database and the collaborated nodes among them. The blocks are performed by these nodes which are known as miners (Taherdoost, 2022). According to Davidson et al., blockchain technology should be seen as an evolution in institutions, organizations, and governance. In fact, although blockchain has traditionally been associated with Bitcoin because of its initial conceptualization by Satoshi Nakamoto in 2008 as the core technology behind the bitcoin cryptocurrency (Walsh et al., 2021, Mai et al., 2018; Zhao et al., 2016), over time, blockchain has slowly moved away from its origins and seen an adoption in a variety of applications (Beck, Müller-Bloch, King, 2018; Kewell&Ward, 2017). Currently, blockchain is predicted to evolve from Blockchain 1.0 for digital currency, Blockchain 2.0 for digital finance, and blockchain 3.0 for digital society (Zhao et al., 2016).

The main characteristics of blockchain technology are decentralization, transparency, security, and the use of a consensus mechanism.

Decentralization. In the blockchain, decentralization implies that the data is evenly available to all participants in the network. The smart contracts are executed peer-to-peer without any third-party or escrow agent involvement, thus making them fraud-proof (Akram et al., 2021)

Transparency. Blockchain is a technology that improves transaction transparency by ensuring that everyone on the network has a copy of the ledger. It is open to every entity in the blockchain for auditing and checking its sanity. To keep their transactions and identities secure, individuals can build private networks with restricted access and select from a list of organizations connected to the blockchain network (Akram et al., 2021).

Security. A cryptography framework comprises a pair of keys, namely, the public key and the private key. Asymmetry encryption enables two keys to validate the authenticity of transactions. During the transaction between the two entities, the public keys can be shared to other entities for receiving the transactions, and private keys must be kept secret (Akram et al., 2021).

Consensus Mechanism. There is a set of rules and procedures that allows for maintaining a coherent set of facts between multiple participating nodes. New transactions are not automatically added to the ledger. The consensus process ensures that these transactions are stored in a block for a certain time before being transferred to the ledger and become unmodifiable (Nofer, 2017).

Blockchains are particularly adept at enabling and tracking transactions, for example via QR (Quick Response) codes or RFID (Radio-frequency Identification) tags, thereby providing provenance of assets and facilitating the initiation of smart contracts (Taylor P. J., 2020).

The reason behind the growing interest in blockchain technology is partly identified in the possibility of knowing the provenance which enables auditing to identify wrongdoing and impose penalties and corroboration to resolve disputes between users. These benefits of blockchain facilitate the trustworthiness of users and provide incentives for them to act honestly in their transactions and recording of events.

Given the importance of the potential use of blockchain in the public sector and to ensure a replicable review process and the validity of the conclusions, a systematic literature review methodology has been applied (Tranfield et al., 2003; Denyer and Tranfield, 2009). According to Frizzo-Baker et al. (2009) a systematic review is an effective exploratory methodology for early-stage research on blockchain. Systematic reviews are a form of meta-analysis designed to collect, investigate, and summarize what is known and what is not known about a "specific practice-related question" (Briner et al. 2009, Frizzo-Baker et al. 2020). They bridge the "research-practice gap" (Rousseau, 2006) and the synthesis of the studies reviewed can be integrated into professional practice (Sackett, 1997) which is the aim of this study.

The first step of the analysis was to identify the research area and topic and then define the keywords that will then be used to extrapolate the information from the databases and determine the review protocol (including, e.g., the inclusion and exclusion criteria of the papers). The subsequent phases were carried out according to the principles for systematic review proposed by Tranfield et al. (2003).

Search process

Based on the research questions the query string was developed by combining research terms: (("public administration") OR ("public sector") OR ("public service)) AND ("waste management") AND (("blockchain") OR ("dlt") OR ("distributed ledger")). Given the scarce number of articles found the authors decided to narrow down the keywords of the query string and adapt them to each of the electronic databases in use. The final query string used resulted in: ("blockchain*") OR ("dlt") AND ("waste management"). Title, abstract, and keywords were used to search published journal papers and conference proceedings on six electronic database resources: IEEE, Google Scholar, JStor, Science Direct, Scopus, and Web of Science. The decision of consulting six different databases was based on the scarce number of articles dedicated to the topic of blockchain technology applied in waste management, and the need to have a sufficiently broad overview of what is the current state-of-the-art in this same research field.

The literature search resulted in 32 articles on Scopus, 33 articles on Web of Science, 15 articles on Science Direct, no results on JStor, 12 results on IEEE and 55 results on Google Scholar until August 21st, 2022.

Afterward, a filtering process was conducted with the inclusion and exclusion criteria shown in Table 1., to examine the literature relevance by reading titles, keywords, and abstracts and selecting the articles closely related to the chosen topic. This process resulted in 24 articles on Scopus, 20 articles on Web of Science, 12 articles on Science Direct, no results on JStor, no results on IEEE, and 12 results on Google Scholar.

Table 2 - Inclusion and exclusion criteria

Inclusion criteria	
Article focus	Works focalized on the analysis of the applications of blockchain technology in waste management which may have a repercussion on the organizational pattern of Public Administrations following the NPG model.
Publication type	Articles, book chapters, conference papers and reviews are considered.
Exclusion criteria	
Article focus	Papers where the discussion is among private sectors not involving public administration such as waste management in the automotive or food sector.
Language	All papers written in a different language than English are excluded.
Availability of information	Exclude all works for which the abstract or the full document is not available.

Source: Author’s own elaboration.

The process of refining the analysis involved the elimination of duplicates that arose during the research on the different databases. Papers were also eliminated if all the information necessary for an analysis of the literature was not available such as papers with no available abstracts. The papers identified were only considered if they were written in English. The detailed selection process led to a shortlist of 32 relevant papers. The authors used Mendeley to collect and categorize the articles resulting from the research and the content analysis software NVivo12 to create a database of articles, code them, and conduct the analyses. First, the whole population has been coded to identify basic information about the papers including the year of publication, the geographical area (country of the authors), the focus of the paper and the research methodologies applied. This process helped the authors to answer RQ1. Then the authors coded the studies to address RQ2 and RQ3.

2.2.2 Analytical Framework

In the following section, the analytical framework of the research is presented. The analytical framework construction is based on the framework adopted by Paoloni and Demartino (2016) in the article "Women in management: perspectives on a decade of research (2005-2015)". In order to fit the research necessities in this systematic literature review, the framework has been adapted including criteria such as the focus of the papers, the geographic area of the authors, and the research method used. Table 2 shows the first criterion is Article focus (A). This category aims at identifying the macro themes analysed in the papers. This type of categorization serves to understand which topics are being discussed in literature, and, as a result, to understand whether there are gaps in this field of research. The categories are based on the different sectors of waste management such as solid waste management, waste management, e-waste management, construction & demolition waste management, rural waste management, water waste management, and plastic waste management. The papers not in line with these categories are categorized as "other". The second criterion is the geographic area of the authors. The analysis of this category serves as an overview of the geographical areas in which blockchain technology in waste management is considered of interest, is already applied, or is about to be applied. The papers with authors are falling under the "mixed" category. The last criterion regards the research methods used in the papers. Among the methods, the qualitative research method has been included although considering that systematic reviews do sit more comfortably with quantitative methods such as controlled trials, quasi-experimental designs, cost-benefit, or cost-effectiveness studies (Engel and Kuzel,1992).

Table 3 - Categorization criteria

A: Research Focus	*B: Geographic Area*
A1. Solid waste management	B1. Europe
A2. E-waste management	B2. North America
A3. Water waste management	B3. South and Central America
A4. Plastic waste management	B4. Asia
A5. Other	B5. Oceania
	B6. Africa
	B7. Mixed
C: Research Methods	
C1. Qualitative method	
C2. Quantitative method	
C3. Case study	
C4. Design Science Research	
C5. Literature review	
C6. Other	

Source: Author's elaboration.

To fully grasp the possible blockchain applications to waste management, two more items to analyse during the review have been identified. The first one being the benefits of blockchain technology in waste management identified in literature, and the second one the challenges and pain points identified. These items were preparatory to answer RQ2 and RQ3.

2.2.3 Results

This section summarizes the results of the systematic literature review.

The first category analysed is the research focus which is based on the different types of waste management identified in the papers reviewed (A). This categorization is based on the need for the PA and municipalities to know how to complete their duties in waste management systems. Under the concept of environmental systems, pollution is viewed as one total system whose manifestation may differ in form: air, water, and solid waste pollution are all interdependent (Lieber, 1970). Thus, for each of the waste categories, there is a different approach to waste management and issues involved in order for PA to guarantee sustainable development (e.g., there are rules and policies on dangerous wastes like hospital wastes) (Damadi et al. 2021). Most of the analysed papers are a study of the application of blockchain technology to solid waste management (A1). Solid Waste Management (SWM) is a multidisciplinary activity, involving several processes related to planning, collection, logistics, monitoring, control, recycling, and disposal of waste (Ratnasabapathy et al., 2019). Blockchain technology provides the possibility of time tracing activities, secure data transactions, and automatic reward systems which makes it a useful technology in this sector. Construction and Demolition (C&D) waste is one of the major parts of solid waste and the second most relevant focus identified during the review process. The construction and demolition waste management focus has been identified in a circular economy (CE) vision by applying blockchain technology. The implementation of the CE principles in the construction and demolition sector may be beneficial for individuals and communities to improve resource productivity. Plastic waste management (A6) and medical waste management (A2) are of similar interest in the papers analysed. The relevance of plastic waste management is due to the consequences of the Covid-19 pandemic which caused an increase in the amount of plastic waste to 1.6 million tonnes per day (Benson et al., 2021, Bhubalan et al., 2022). Around 9 million tonnes of pandemic-associated waste were generated by 193 countries as of August 2021 due to increased consumption of masks, sanitizer bottles, and online delivery packaging (Peng et al., 2021, Bhubalan et al., 2022). During the review, the authors identified a link between plastic waste management and recycling systems implementing blockchain. The construction and demolition waste management focus has been identified in a circular economy (CE) vision by applying blockchain technology. The implementation of the CE principles in the construction and demolition sector may be beneficial for individuals and communities improving resource productivity. E-waste management (A3) is the least studied topic in the presented review. Electronic waste (e-waste) presents a complex challenge to the growing field of circular economy (CE) (Salmon et al., 2021). Electronics are responsible for significant impacts across their life cycle. This starts with the extraction of a diverse mix of valuable, scarce, and hazardous raw materials (Greenfield and Graedel, 2013, Salmon et al., 2021); continues with the energy-intense manufacturing of components (Deng et al., 2011; Williams, 2004, Salmon et al., 2021); and ultimately ends with a complex, continuously evolving e-waste stream (Althaf et al., 2020, Salmon et al., 2021). Due to the information asymmetry between the regulators and regulated institutions, problems such as illegal dumping and statistical fraud are common in hazardous waste transfer (HWT) activities which regard all the aforementioned waste management sectors (Song et al., 2022).

To analyse the research methods most applied to waste management and blockchain studies, the authors identified a primary selection of quantitative and qualitative research method-based papers. Most of the articles are based on qualitative research (C1). A trend of Design Science Research (DSR) with a proof-of-concept (POC) representation has been identified (C4). The DSR papers are usually focused on the interoperability between blockchain and IoT and the use of automated systems (e.g., Smart bins). The second most applied research method is literature review (C5). The literature reviews are usually focused on one of the aforementioned waste management sectors rather than waste management in general. Lastly three case studies have been identified (C3).

Geographical area of author's affiliations

The analysis of the geographical area of the author's affiliations shows how Asia is the area where blockchain technology application in waste management is most studied. In particular, the country most encountered in Asia among China, India, Indonesia, Pakistan, The Emirates and Turkey is India. The second most encountered geographical area is Europe. North America (United States of America) and Oceania (Australia) are both on the same level of frequency, while only one paper has been identified in the South America geographical area.

2.2.4 Discussion

The first outcome of the literature review is linked to the total number of papers and the time frame of publication found on the topic of blockchain technology applied to waste management as an alternative to the traditional approach. Although the authors did not choose a specific time frame while creating the article database, the presence of articles focusing on blockchain in waste management is found mainly from 2018 onwards. The small number of papers and the year of publications show how the topic is still relatively new in literature, which indicates that several research gaps are yet to be addressed in order to fully comprehend the impact of blockchain technology on waste management and consequentially the PA organization and strategies. The papers analysed in the review process result being written mostly by authors from the Asian geographical area. The reason behind this is to be found in the impact of waste on Asian communities where the population density results high and waste production is constantly growing, e.g., India's population density goes from 100 people per sq. km to 1000 people per sq. km (Karuppannan et al., 2020).

The most frequently identified research focus during the review process has been that of solid waste management which includes several aspects of waste management and is fundamental to address in the governance process of municipalities. It is a key administrative unit for managing urban waste to deliver an eco-friendly environment to the citizens residing in urban cities (Akram et al. 2021). Blockchain technology is identified as the solution for fraud prevention (Salmon et al., 2021), for incentivizing individuals to correct disposal of waste, but also for data sharing and management, to digitalize documentation of activities such as waste generation, waste collection, and recycling (Akram et al., 2021). As for the research methodologies, the DSR method has been most applied, yet there is a need of more empirical research. According to França et al. (2021), a continuity of research should involve testing systems in real operating environments, and developing the studies based on Science Design Research.

Blockchain technology offers a means to decrease the level of supervision and lying costs (Salmon et al., 2021). The main applications of blockchain in waste management analysed in literature are identified in data sharing and management (Ratnasabapathy et al. 2019, Pellegrini et al. 2020, Taylor et al. 2020, Akram et al. 2021), reward-based systems, fraud prevention, and real-time waste collection.

The presence of an electronic database and the electronic sharing of information relating to waste makes it easier to record all data relating to the life cycle of materials and products, improving the related control activities, and increasing collaboration among them (Pellegrini et al. 2020). In waste management, blockchain technology is utilized to implement the digitalized documentation of activities such as waste generation, waste collection, and recycling (Akram et al. 2021). Due to the traceability of data written and shared on blockchains recyclers can keep track of the waste generated as it moves through the various chains. Consumers can also use the public ledger information to make more informed product purchasing decisions (Khadke et al. 2021). Furthermore, blockchain data cannot be edited, it is, therefore, important to have robust protocols for recording transactions, such as automating the process using complementary technologies or requiring digital signatures from all parties involved in a transaction (Taylor et al. 2020).

Reward-based systems (Zhang 2018, França et al. 2021, Akram et al. 2021, Sen Gupta et al. 2021), motivate individuals in the correct disposal of waste. An organization employing a smart waste management and a reward-based system can allow the recycling of waste and promote sustainability. From a government perspective, monetary government services and products can be allowed to be paid off using the tokens, thus increasing market demand of the tokens, which in turn motivates users for waste segregation (Sen Gupta et al. 2021).

The use case presented by França et al. is a relevant example of the possible use of blockchain technology in solid waste management. The article entitled "Proposing the use of blockchain to improve the solid waste management in small municipalities" presents the possible application of Ethereum's Blockchain digital architecture in a small municipality in the State of Sao Paulo, Brazil. The use case presented uses crypto-coins and security support through Ethereum's Blockchain, to replace a paper-based system where low-income households get the so-called Green Coins in exchange for their selected solid waste which is used by local registered traders. The aim is to incentivize citizens to a correct solid waste collection process through the possibility of buying assets with the Green Coins and for the Municipality to sell solid waste to recycling companies. The main limitation of the paper-based system was the integrity assurance and fraud protection, due to the costs associated with antifraud security items. The use of social cryptocurrencies supported by Blockchain innovates the standards of negotiation between collectors and local commerce, as well as the reliability and trustworthiness in the monetary transactions bringing benefits to public administrations.

The interest in literature for a social-currency system is currently growing and the benefit of a social cryptocurrency is identified in a different view of the collection and disposal of waste which, from being a hassle, may be viewed as economically worthwhile (Zhang D. 2018).

Another incentivizing use case is presented by Akram et al. with an automatic reward system to individuals for the disposal of waste in smart bins. Smart bins are bins where a sensor node can communicate data to a cloud server via a gateway. Interoperability is the key to making the system work. IoT and a blockchain network are linked for a real-time implementation where the IoT devices of the bins monitor data in real-time and the weight of the bins creates new transactions in the blockchain network.

Immutable record-keeping technologies like blockchain are also a solution to fraud prevention aligning behaviors across recyclers and towards a circular economy (Salmon et al. 2021).

Lastly, real-time collection of waste from bins once they are full and real-time disposal of waste from vehicle to disposal area if the vehicle container is full are of interest in research. Real-time decision-making is a priority in a smart and sustainable city (Gupta et al. 2019, Gupta et al. 2021).

According to the papers analysed blockchain applications in waste management represent an advantage for the PA. Yet, the assumption that all entities may cooperate and agree to be part of a common blockchain system may be a limit to its fruitful application. Furthermore, a significant challenge for blockchain systems is implementing governance and determining a process for maintenance and upgrades (Scott et al., 2021). Among the possible challenges that the PA might find in the attempt of implementing blockchain technology to waste management in their organizational and strategic processes the lack of education and training of those actively using the applications and the lack of regulations are two of the most frequently identified (Ongena et al., 2018, Pucihar et al., 2018, Zhang et al., 2018, Torkayesh et al., 2021, Khadke et al., 2021). Nonetheless, blockchain data cannot be edited, incorrect additions cannot easily be fixed, and the ownership of data must be clearly defined from the beginning. The data entered on the blockchain must be correct. The type of responsibility and whether it transfers with ownership may be set out in laws and policies, but gray areas exist (Taylor et al., 2020). Yet Mori found that 20% of the barriers to the application of blockchains are due to technical reasons (Song et al., 2022). In comparison, another 80% are due to current business processes, modes, and management systems (Mori 2016). Therefore, the main challenge in applying blockchain to waste management is the current business processes and the lack of institutional innovation (Song et al., 2022) or, even more important, the presence of Internet around waste facilities to transform the required data.

Sustainable development is being approached as a new economic paradigm that establishes a general context for organizations and institutions to develop their strategies and processes. This is particularly true for PAs, where a change process is taking place towards the development of sustainable and smart cities. The NPG paradigm states that innovation plays a fundamental role in PAs, and it is a means through which it is possible to achieve service efficiency and effectiveness and the base for the structuring of a sustainable business model of PSOs (Brown, Osborne, 2015). The alignment between municipal waste management policies and strategies and its operations is fundamental, in order to build a strategic vision based on sustainable development that guides performance results (Sukholthaman et al., 2017, Wilson et al., 2015, Mendes et al., 2012, Rodrigues et al., 2018). Blockchain can favor the adoption of circular practices thanks to a double integration that clearly identifies those responsible for the entire lifecycle of waste flows, with a reduction in management costs and control time (Centobelli et al., 2021, Krajnakova et al., 2019). In fact, the concept of blockchain is often defined as "a technology for sustainability transformation of the linear economic paradigm" (Centobelli et al., 2021, Bockel et al., 2021). Blockchain technology and the circular economy are the two emerging concepts that will revolutionize lives in the upcoming decades as blockchain provides transparent information and reliability to the circular economy system (Khadke et al., 2021). Nonetheless, blockchain technology can facilitate the incorporation of good governance characteristics: participation, transparency, responsiveness, effectiveness and efficiency, and accountability (Steenmans K. et al 2021). Blockchain can completely change the way people manage environmental resources and help promote sustainable development (Herweijer et al. 2018). Blockchain is also a tool to incentivize individuals in following the correct process in the disposal of waste through certified reward systems using tokens and social cryptocurrencies. Overall, the implementation of smart contracts and IoT bring government agencies and stakeholders on the same blockchain platform improving monitoring and transparency in the waste management processes

(Kassou et al 2021). All of the aforementioned are blockchain applications that have the potential of impacting positively both the organizational and managerial flow of activities, and the sustainable development of cities and communities.

A circular economy offers a promising alternative to the traditional linear "cradle-to-grave" approach, replacing it with a "cradle-to-cradle" model. This economic framework aims to minimize reliance on virgin resources while reducing waste generation and emissions from economic activities (Bhubalan et al., 2022). The transition to a circular economy requires integrating advanced technologies, policies, and community engagement to ensure effective and sustainable waste management practices. Blockchain technology, a key driver of digital transformation in the 21st-century economy, plays a pivotal role in advancing circular economy principles. As a decentralized, tamper-resistant digital ledger, blockchain enables secure and permanent data storage without reliance on a central authority. Its application in waste management facilitates the creation of circular economies by automating transactions and record-keeping, reducing reliance on intermediaries. For instance, blockchain combined with molecular tagging can enhance plastic waste management by enabling chemistry-based redesign of plastic materials (Bucknall, 2020). Beyond plastics, blockchain can also improve the management of biopolymer waste by tracking and preventing improper disposal. The introduction of biodegradable plastics into waste streams without proper technical handling, infrastructure, and consumer awareness can complicate waste management efforts (Hopewell et al., 2009). Recognizing the potential of blockchain, the European Union has established the EU Blockchain Observatory and Forum to drive innovation and position Europe as a global leader in blockchain technology. Effective blockchain implementation requires clear communication of its benefits and limitations to the public. Overcoming existing barriers is essential to maximize its potential. In plastic waste management, integrating blockchain with efforts to increase the specification and use of recycled plastics should be a top priority to mitigate environmental and economic challenges (Bhubalan et al., 2022). However, widespread adoption of blockchain technology in waste management requires supportive regulatory frameworks, investment in digital infrastructure, and community engagement to ensure seamless implementation and long-term sustainability. Improper waste management in rural areas of developing countries contributes significantly to environmental contamination (Han et al., 2019). Many rural communities lack adequate waste collection and treatment facilities, leading to open dumping and burning, which pose severe health and environmental risks. In Indonesia, the treatment of categorized rural household waste is a crucial component of the nation’s Rural Revitalization Strategy, addressing the population’s need for a cleaner environment (Abidin et al., 2022). When planning the placement of garbage collection sites, special attention must be given to the spatial distribution of rural residential areas. This reduces the time and energy spent by residents on waste classification and recycling, ultimately promoting waste reduction, resource utilization, and safe disposal (Cui et al., 2024). Moreover, integrating digital tools, such as geographic information systems (GIS) and artificial intelligence (AI), can optimize waste collection routes, improving efficiency and reducing costs. Technological innovations such as the LoRa network for IoT-enabled smart waste bins offer solutions for sorting organic and inorganic waste while monitoring volume, gas content, and weight. These systems can adaptively place waste bins based on location-specific parameters and rural disposal practices (Abidin et al., 2022). However, disparities in internet accessibility and digital literacy remain a significant challenge in many rural communities. While some individuals primarily use the internet for entertainment, others engage in educational or agricultural forums, which provide varying levels of exposure to waste management practices. To bridge this gap, initiatives should focus on improving digital literacy and ensuring equitable access to internet resources. Mobile internet has the potential to enhance rural digital governance capabilities. The "Internet Plus" concept in environmental governance facilitates digital waste management across sorting, collection, transportation, processing, supervision, and feedback stages. A Chinese case study highlights how social media platforms such as WeChat, Weibo, and short video apps effectively promote environmental awareness among rural residents (Wang et al., 2024). Expanding such digital initiatives could drive behavioral change and foster community participation in sustainable waste management. Rural communities' attitudes toward waste management are crucial for successful implementation. While blockchain technology offers a solution, understanding managerial perspectives is essential. If initial resistance exists, demonstrating blockchain's efficiency in waste tracking and transparency may shift attitudes. Classifying household waste is a critical step toward promoting eco-friendly lifestyles, with studies showing that sorted collection and treatment significantly enhance waste management. Farmers, as primary producers of rural household waste, play a decisive role in classification efforts. Their willingness and behavior directly influence the success of waste management initiatives. Strengthening rural communities through social networks and self-governance fosters intrinsic motivation for environmental participation. Enhancing informal community structures and promoting self-organization can encourage rural residents to adopt waste-sorting behaviors. By integrating binding community norms, rural waste management initiatives can gradually gain traction (Wang et al., 2024). Policies should align with rural inhabitants' cultural backgrounds, reinforcing normative waste management behaviors. Community leaders play a crucial role by advocating for sustainable practices and fostering collective digital engagement (Wang et al., 2024). Information and Communication Technology (ICT) holds significant potential in waste management. In Punjab, dairy farmers access organic waste management information through ICT tools, underscoring the need for further technological development to support sustainable waste practices (Singh et al., 2022). Participatory learning models, such as India's farmer field schools, have demonstrated their effectiveness in disseminating specialist knowledge, skill development, and farmer empowerment (Singh et al., 2022; Bajwa et al., 2010). Expanding such educational initiatives can improve waste management practices and promote long-term sustainability in rural communities. Access to sustainable energy services is essential for smart village development, enabling efficient management of energy, water, and waste. Rural areas often function within clustered settlements, presenting opportunities for localized competitive advantages. The "rurban" concept integrates physical infrastructure, economic services, and waste management systems. The IEEE Smart Village network supports smart village design and technological innovation, enhancing community participation in sustainable practices. A key aspect of waste management in smart villages is optimizing waste collection and disposal. Traditional methods require garbage collectors to manually check bins, consuming human effort, time, and fuel. Smart bins equipped with sensors can automate waste level monitoring, improving efficiency and resource allocation. Implementing these technologies in rural areas can significantly enhance waste management efficiency while reducing environmental impact. While household waste classification and treatment are vital for environmental sustainability, a gap often exists between rural residents' willingness to classify waste and their actual practices. Internet usage has been shown to reduce this discrepancy by enhancing ecological awareness and knowledge perception. However, in suburban villages and communities with existing environmental governance projects, internet influence on waste classification remains limited. Comprehensive policies must address these gaps by investing in rural internet infrastructure, strengthening waste classification regulations, and implementing reward-and-punishment systems to encourage participation. A points-based waste classification system could further incentivize compliance, ensuring long-term behavioral change toward sustainable waste management. Integrating digital tools, blockchain technology, and community-driven initiatives will be essential to fostering an inclusive and effective circular economy. Advancing sustainable waste management requires a multi-faceted approach that integrates technology, policy, and community engagement. Blockchain technology, ICT solutions, and digital governance offer transformative potential in improving waste management systems, particularly in rural areas. However, successful implementation depends on addressing technological barriers, fostering behavioral change, and aligning strategies with cultural and socioeconomic contexts. Future efforts should focus on expanding digital literacy, enhancing policy frameworks, and leveraging innovative technologies to build resilient and sustainable waste management systems.

Chapter 3. Waste management Practices and Challenges in Italian rural areas

This chapter describes the RWM practices in Italy exploring the history of waste management policies, the directions of European policies and the current waste management innovations. Specifically, paragraph 3.1 describes waste management in Italian rural areas and discusses the historical context of waste management in Italy. Paragraph 3.2. discusses current waste management practices. Paragraph 3.3 presents an overview of European and national regulations underlining the gaps and challenges in waste management policy making.

3.1 Waste Management in Italian Rural Areas

The challenges associated with rural waste management receive less attention in academic discussions compared to urban regions. This is mostly due to the scares availability of data related to rural areas (Mihai, 2018). Nonetheless, annually, over two billion tonnes of municipal solid waste (MSW) are produced worldwide (UNEP, 2024). This municipal waste arises in areas with human habitation, resulting in considerable quantities of agricultural, construction and demolition, industrial and commercial, and healthcare waste. Such waste is generated on farms, construction sites, in factories, and within hospitals (UNEP, 2024).

Waste management itself can be viewed as a complex, adaptive system that interacts with its environment and evolves in response to external changes (Clayton, 2018). While many studies have focused on municipal solid waste (MSW) management in large cities and metropolitan areas (Mazzanti et al., 2008; Rada et al., 2008; Ranieri et al., 2014), small municipalities have often been overlooked. Yet, in Italy, approximately 69,9% of municipalities are small villages with fewer than 5.000 inhabitants (ANCI, 2024).

The Italian landscape has its own characteristics which have been addressed in the scientific and political context. Italian Geography has been trying to explore the role of peripherical areas within the process of territorial development (Ivona et al., 2021). Historically, Italy has been marked by significant socio-economic disparities between the more developed Northern and Central regions and the less developed Southern areas. These territorial inequalities are also evident in the adoption and distribution of environmentally sustainable waste management practices. Such disparities are reflected in the varying performance levels of waste management systems across different macro-regions (Musella, 2019).

The interest in the areas beyond the cities started from the southern regions with the aim to revalorize the areas in terms of development considered marginal. These areas, mainly Inner Areas and small villages have been subject to the planning of structural measures dictated by emergencies or contingencies (e.g. Cassa per il Mezzogiorno).

In time, several policies have been working towards the increase in number of local communities to become sustainable and responsible realities. Specifically, the settlement network of Italian small towns (the so-called "borghi", with a population lower than 5.000 inhabitants) since 2013 have been object of the National Strategy for Inner Areas (SNAI, Strategia Nazionale per le Aree Interne), aiming at building coordinated, multi-scalar projects of self-enhancement. Furthermore, The European Parliament promoted a 2021-2017 programming period for the European Regional Development Fund following the Italian strategy. These initiatives became the building blocks of a bottom-up approach in small towns and Inner areas where local players have maximized opportunities and attracted tourists with their uncontaminated environments, ancient knowledge and genuine flavours (Ivona et al., 2021).

The rise in rural tourism in Italy provides economic and social advantages to rural communities; however, it also leads to environmental issues, particularly in terms of waste production and the consumption of rural resources (Bux, 2023). It is a closed circle: natural-ecological dimension is acknowledged as an important aspect of the tourism landscape, therefore effective waste management and the abundance of biodiversity are essential for advancing rural tourism (Piras et al., 2025).

Furthermore, in rural regions, waste production is often not accompanied by effective collection strategies, largely because individual homes are dispersed across vast areas, hindering public authorities from delivering comprehensive services due to the expenses and logistical challenges posed by this type of housing arrangement (Passarini et al., 2011).

In Italy, local governments are responsible for determining the measures to implement within their jurisdictions and play a vital role in fostering sustainable waste management strategies. The small municipalities that collaborate experience reduced expenses for their waste collection services. While inter-municipal agreements lead to cost savings, outsourcing does not. Additionally, collaboration increases collection frequency and enhances service quality in smaller towns (Hall & Nguyen, 2012). Furthermore, expanding waste collection into less populated regions contributes to a decrease in illegal dumping practices (Podgaiskyte et al., 2014). Illegal waste disposal is one of the main activities of ecomafias in Italy. The Apulia region ranks among the top at the national level, with an annual average of 3.600 recorded environmental crimes (Glynn et al., 2025)[11].

Finally, sustainable waste management is fundamental working towards the Sustainable Development Goals (SDGs) and it is linked to all the 17 points as declared by the United Nations Development Programme in 2023 (Tab. 4). Effective waste management is a cornerstone of sustainable development and is intricately linked to the achievement of the United Nations Sustainable Development Goals (SDGs). Despite its critical importance, many aspects of waste management remain underdeveloped, particularly in low-resource settings where informal waste workers often operate without health insurance, legal protections, or fair compensation, typically earning only the value of the materials they recover. This leaves them vulnerable to exploitation and perpetuates cycles of poverty and marginalization (SDGs 1, 8, 10). Inclusive municipal waste policies can mitigate these risks by formalizing labor conditions and reducing environmental inequalities.

[11] In Italy (2008) the European Union (EU) Commissioner to the Environment warned that waste disposal was a problem far from limited to Campania. The European Court of Justice in Luxemburg charged Italy for the existence of 4,866 illegal or unmonitored landfills in 15 regions: Abruzzi (361), Basilicata (152), Calabria (447), Campania (225), Emilia Romagna (380), Lazio (426), Liguria (305), Lombardy (541), Marche (244), Molise (84), Piedmont (335), Apulia (599), Toscana (436), Umbria (157), Veneto (174) (Ansa News Agency 2007).

However, addressing both intragenerational and intergenerational disparities requires comprehensive waste and resource management systems supported by multi-stakeholder cooperation, as the transition to a circular economy will not occur organically or equitably (SDG 12).

Globally, the scale of food waste represents a parallel crisis: approximately one-third of all food produced is lost or wasted, even as hunger rates continue to rise (SDG 2). Solutions must include food waste prevention, redistribution of surplus food, and the conversion of unavoidable organic waste into compost or biogas. These practices can restore soil fertility (SDG 15), support sustainable agriculture, and contribute to renewable energy access in off-grid areas (SDG 7). At the urban level, universal access to waste management is fundamental to ensuring safe, resilient, and inclusive cities (SDG 11). Inadequate services often lead to open dumping and burning, practices that release toxic pollutants and significantly impact public health, particularly that of women and children who are more exposed due to gendered roles in household waste management and limited participation in decision-making processes (SDGs 3, 5).

The lack of institutional capacity is further exacerbated by the scarcity of waste management education and training in higher education, resulting in a shortage of skilled professionals able to implement innovative and technically sound solutions (SDG 4). Meanwhile, production and consumption patterns continue to accelerate waste generation, requiring urgent behavioral and systemic changes from governments, industries, and consumers alike. Poorly managed waste also contributes directly to climate change, emitting methane from landfills and black carbon from burning sites, both of which are potent greenhouse gases (SDG 13). Rural and remote areas, particularly in developing nations and Small Island Developing States, face unique waste management challenges, with terrestrial environments and freshwater systems often acting as unregulated sinks for waste, threatening ecosystems and livelihoods (SDGs 6, 14, 15).

Additionally, pollutants from land-based waste sources can enter the marine environment, emphasizing the need for integrated mitigation strategies. Combining municipal solid waste systems with container-based sanitation can enhance service efficiency and attract investment by leveraging economies of scale. Recognizing the increasingly global nature of waste management, international cooperation is essential for capacity building, hazardous waste control, and combating illegal trafficking (SDG 17). At the same time, decentralized waste systems offer the opportunity to foster domestic technology development, entrepreneurship, and private sector participation, while reducing financial burdens on local authorities (SDG 9). Strategic investment in the sector currently insufficient is crucial to manage growing waste volumes and to unlock the full potential of waste management as a driver of resource efficiency, climate resilience, and inclusive economic growth.

Table 4 - Waste Management in SDGS.

1 NO POVERTY	Waste workers in informal economies who have no health or social protections are vulnerable to exploitation and are paid only the material value of the materials they collect. Inclusive municipal waste management policies are most effective for addressing both poverty and pollution.	10 REDUCED INEQUALITIES	Intragenerational and intergenerational inequalities must be addressed through developing waste and resource management systems; attention is required from all stakeholders because the transition to a more circular economy will not occur by default
2 ZERO HUNGER	While global hunger is increasing, one third of all the food grown in the world is wasted. Hunger can be reduced by preventing food waste and redistributing excess food. Converting unavoidable food waste into compost can replenish depleted agricultural soils.	11 SUSTAINABLE CITIES AND COMMUNITIES	Solid waste management is a basic utility service without which air quality and living conditions become degraded, leading to poor health and social discontent. To make cities and communities inclusive, safe, resilient and sustainable, universal access to municipal waste management services is essential.
3 GOOD HEALTH AND WELL-BEING	Communities without adequate municipal waste management services resort to dumping and open burning, both of which have significant negative health consequences, particularly for women and children.	12 RESPONSIBLE CONSUMPTION AND PRODUCTION	Production and consumption patterns directly impact municipal waste generation. To reduce waste and prevent pollution, efforts are needed by companies, governments and citizens.
4 QUALITY EDUCATION	Waste management courses in tertiary and higher education are uncommon, resulting in a lack of professional technical capacity and a shortage of workers with appropriate skills and knowledge.	13 CLIMATE ACTION	Poorly managed waste generates a wide range of emissions that contribute to climate change, most significantly methane from landfills and dumpsites, and black carbon and a range of other emissions from the widespread practice of the open burning of waste.

5 GENDER EQUALITY	Experience with waste and its management is gender-differentiated: e.g. household purchasing and domestic waste-generating activities, and levels of influence over community decision-making regarding waste collection services.	14 LIFE BELOW WATER	Understanding why and how land-based waste reaches the sea, and introducing mitigation measures, is essential. Urgent action is particularly required in the case of Small Island Developing States, which face a complex set of waste management challenges.
6 CLEAN WATER AND SANITATION	Pollutants leaching from dumpsites can contaminate freshwater sources and associated food chains. Meanwhile, combining municipal solid waste and container-based sanitation services can achieve economies of scale that make both services more attractive to investors.	15 LIFE ON LAND	: The terrestrial environment continues to be the primary sink for waste, while rural communities face complex waste management challenges that if left unmanaged can significantly impact ecosystems and dependent livelihoods.
7 AFFORDABLE AND CLEAN ENERGY	Unavoidable food waste can be used to make biogas, a clean-burning renewable fuel that could be used to tackle energy poverty, including in off grid communities.	16 PEACE, JUSTICE AND STRONG INSTITUTIONS	The increasingly global nature of waste management calls for heightened international cooperation to build national capacity for the safe management of hazardous waste and to prevent its illegal trafficking
8 DECENT WORK AND ECONOMIC GROWTH	The waste management and recycling sector is uniquely positioned to improve global resource efficiency, decouple economic growth from environmental degradation, and provide safe and decent work opportunities for all.	17 PARTNERSHIPS FOR THE GOALS	Current investments in waste management are insufficient. Far higher investments will be needed in the future to cope with increasing waste generation and the accumulation of legacy waste. The return on investment for waste management needs to be realised to catalyse increased finance.
9 INDUSTRY, INNOVATION AND INFRASTRUCTURE	Decentralised waste management systems can attract private sector investment, encouraging innovation, entrepreneurship, domestic technology development, greater resource efficiency and increased employment opportunities, and reduce financial risks for governments and municipalities.		

Source: adaptation from United Nations Environment Programme 2023

To tackle the sustainable development goals this research is focusing on the local communities which is where sustainable practices should start according to the United Nations (SDG 11).

Waste management is usually the responsibility of local authorities, which have limited resources, especially where municipalities are not populated by high-income individuals (Mazzanti et al., 2008;

Chu et al., 2019). This has a negative bearing on the capacity of the authorities for waste management planning, contracting, operational monitoring, and so on. Moreover, inter-municipal government cooperation is in place in a minority of cities only; its impact on waste collection and sorting is limited, as it typically occurs through the us of shared assets for waste transfer, disposal, and city cleaning (Kaza et al., 2018). Sparsely rural areas which are remote from major urban areas are usually the most neglected by waste management services. Waste operators avoid such areas, and local authorities provide no or low financial resources to provide appropriate public services. In addition, the geographical constraints (mountains, hills, etc.) makes it more difficult to implement proper waste management facilities (El-Haggar et al., 2007).

This section aims to enhance understanding of how waste management is implemented at the municipal level, with a particular emphasis on the quantitative aspects of solid waste sorting and its subsequent transfer to treatment facilities. A key point of interest is whether waste sorting and treatment activities can be effectively monitored using available data. To gain clearer insights into the specific needs and obstacles encountered by local communities, this chapter explores the core characteristics of Italian waste management policies and practices, especially as they affect rural areas. A future objective is to explore how waste management systems can be better adapted to the unique socio-economic and geographical conditions of small rural municipalities. In particular, the study seeks to: (1) evaluate the strengths and weaknesses of current waste management strategies in these areas; (2) highlight successful practices and innovative local initiatives; and (3) develop policy suggestions to support more equitable and sustainable waste management throughout all Italian regions.

3.2 Role of EU regulations in shaping local practices

Waste management systems respond to the complexity of connections among policies, regulations, socio-cultural contexts, environmental conditions, economic development and available resources

(Cohen et al., 2021). As in other European countries, waste management performance in Italy is strictly related to EU recycling targets (Greco et al., 2015). Over the last two decades, the European Union (EU) Directives have set waste policies and targets to deal with waste issues in a coordinated way considerably them (Bourguignon et al., 2018). First, to reduce landfill burial or limit its expansion, the EU Landfill Directive (EU Directive 99/31/EC) was introduced in 1999. Later the EU Waste Framework Directive (EU Directive 2008/98/EC) established a "waste-management hierarchy", ranking recovery, and landfill burial (Wang, 2020). The waste management hierarchy is the basis for sustainable MSW management and the selection of indicators, such as recycling, recovery, and landfill rates, to assess whether such management has been achieved (Haupt et al., 2017; Pomberger et al., 2017; Zaccariello et al., 2015).

The Waste Framework Directive establishes a hierarchical model for waste management, which prioritizes actions based on their environmental impact. This hierarchy consists of five levels: prevention, preparation for reuse, recycling, recovery, and disposal. The current study concentrates on the last three recycling, recovery, and disposal due to the availability of relevant data. At the top of the hierarchy is waste prevention, recognized as the most favorable strategy. Prevention involves proactive measures to ensure that materials, products, or substances are not turned into waste, such as through product life extension or promoting reuse. Article 9, Chapter 1 of the Directive mandates that all EU member states develop waste prevention programs that aim to decouple economic growth from the environmental burden of waste generation (Directive 2008/98/EC). However, due to limited data and resources, this thesis does not address waste prevention in detail.

The second level, preparation for reuse, involves recovery operations like inspecting, cleaning, or repairing products so they can be reused without additional processing. According to Article 3, Chapter 1 of the Directive, member states are required to encourage reuse, including through re-use networks and standard-setting for production materials. Despite its importance, this area is also excluded from the analysis due to insufficient data.

Recycling, the third tier of the hierarchy, plays a crucial role in the European Union's shift towards a circular economy. Defined in Article 11 as the reprocessing of waste materials into new products, substances, or materials, either for the original or a different purpose recycling is central to current EU waste management strategies. The 2025 revision of the Directive strengthens the obligations of member states to promote high-quality recycling through efficient, separately managed collection systems for waste types such as paper, glass, metals, and plastics. Beginning in 2025, this requirement will expand to include textiles and hazardous household waste. Furthermore, the revised directive sets ambitious targets: by 2025, at least 55% of municipal waste by weight must be prepared for reuse or recycling, increasing to 60% by 2030 and 65% by 2035. These targets also apply to packaging materials. The directive aims not only to enhance resource efficiency and reduce environmental impacts but also to foster innovation in the recycling sector, thereby supporting the broader objectives of the European Green Deal and the Circular Economy Action Plan.

Waste recovery constitutes the second preferred option within the waste management hierarchy. This process entails the conversion of non-recyclable waste materials into valuable outputs, predominantly through energy generation. Pursuant to the 2025 amendment of the Waste Framework Directive (Directive 2008/98/EC, as amended), recovery operations are permissible exclusively where the waste does not comprise recyclable fractions such as paper, plastics, or textiles that are now subject to mandatory separate collection requirements. Eurostat (2023) classifies recovery into three categories: material recovery, backfilling, and energy recovery through incineration. This research focuses on waste-to-energy incineration, a process that generates electricity or heat by combusting waste. The incineration process produces two main by-products: fly ash and bottom ash. Fly ash, which is captured from flue gases, contains hazardous substances including heavy metals, making it difficult to handle or repurpose. Conversely, bottom ash, which remains on the incinerator grate post-combustion, is generally less toxic and can be recycled as a building material, such as in road construction. The 2025 directive revision emphasizes minimizing the environmental footprint of incineration, promoting the beneficial reuse of bottom ash within circular practices, and ensuring that fly ash is treated in accordance with stricter environmental regulations.

EU is also making the requirements about separate waste collection more stringent, for instance, by specifying exemptions in further detail and requiring separate collection for textiles and hazardous waste from households by 2025.

Furthermore, the Traceability Directive of the European Union has been formally incorporated into the broader EU waste legislation. It pertains to a collection of regulatory measures designed to ensure the clear and ongoing monitoring of waste throughout its entire lifecycle. Integrated within the Waste Framework Directive (2008/98/EC) and strengthened by subsequent regulations such as the Regulation on Waste Shipment (EC Regulation No. 1013/2006), these provisions require that all parties involved in the generation, transport, treatment, and disposal of waste keep precise records. This system of traceability is essential in the fight against illegal waste trafficking, enhances environmental protection, and supports the principles of a circular economy (OECD, 2024, April 26). Recent initiatives, including proposals under the European Green Deal and the Circular Economy Action Plan, seek to digitize and unify waste traceability across member states through electronic data systems, thus improving enforcement and compliance.

3.3 Overview of National Waste Management Policies

The Italian Decree of 1997 followed a few European directives of 1991 and 1994, which provided frameworks for waste management in the EU (see the directives 91/156/CEE, 91/157/CEE, 91/689/CEE, and 94/62/CE). These are the most relevant pieces of Italian legislation - the so-called Ronchi Law, after the name of the Minister of Environment, aimed at introducing several remedies to salient environmental issues arising from waste management. Those issues included a remarkable increase in the amount and variety of waste; growing demand for waste disposal; and increasing risk of negative environmental, health and social impacts of waste management practices.

Furthermore, the Legislative Decree n. 152 of 2006 of the Environmental Code clarified the different authorities regarding waste management ascribing specific duties to the different institutional levels (i.e. central, government, regions, provinces, and municipalities) (Bonelli, 2016).

Additionally, in June 2022, Italy adopted the National Waste Management Plan (Programma Nazionale per la Gestione dei Rifiuti), as envisaged by the WFD and Italy's National Recovery and Resilience Plan. The National Waste Management Plan defines the medium - and long-term objectives criteria and strategic guidelines of the development of regional waste management plans ("Piani Regionali di Gestione dei Rifiuti") to ensure that waste management policies are aligned with EU Directives and across all levels of government.

On the other hand, National Recovery and Resilience Plan (PNRR), a €750 billion initiative, is designed to facilitate a green, ecological, and inclusive transition by promoting the circular economy, renewable energy development, and sustainable agricultural practices (European Commission, 2021a). Within this context, the valorisation of organic waste, such as through waste-to-energy and waste-to-bioproduct conversion, should be considered a strategic component. Specifically, under Mission 2 of the PNRR, referred to as the "Green Revolution and Ecological Transition," targeted interventions aim to enhance separate waste collection systems and improve infrastructure for the treatment and recycling of organic waste (European Commission, 2021b).

In parallel, the Common Agricultural Policy (CAP) is characterized as a partnership between agriculture and society, and between the European Union and its farmers. It seeks to preserve rural areas and landscapes across Europe while supporting rural economies by promoting employment in agriculture, the agri-food industry, and related sectors (European Commission, 2021c). Moreover, the CAP includes objectives for climate change mitigation and adaptation, including reducing greenhouse gas emissions, enhancing carbon sequestration, encouraging sustainable energy use, and lowering chemical inputs in farming (European Commission, 2021d).

In alignment with the European Circular Economy Action Plan and EU regulations, the new national strategy introduces a comprehensive approach to advancing sustainable waste management. Key components of the strategy include the implementation of a digital waste traceability system, fiscal incentives to support recycling and the use of secondary raw materials, and revisions to the environmental taxation framework. Additionally, the strategy emphasizes recognizing the right to reuse and repair, an important aspect of fostering a circular economy. Reforms to extended producer responsibility are also central to the strategy, alongside the reinforcement of existing regulatory tools, including legislation on the "end of waste" status and the establishment of minimum environmental criteria for green public procurement. In line with these objectives, the strategy aims to support industrial symbiosis projects, which encourage cooperation between industries to optimize resource use and reduce waste (National Strategy for Circular Economy - M2C1.1-R.1.1-1, 17decies).

Furthermore, Italy's National Strategy for the Circular Economy ("Strategia Nazionale per l'Economia Circolare"), adopted in June 2022, recognizes the need for urgent action to place the country on a path towards a sustainable circular economy and to unlock the environmental and climate benefits of the transition. The strategy recognizes the potential of circular economy to contribute to the policy objectives of securing supply of raw materials, domestic competitiveness and job creation. Among the core objectives a new system of waste traceability has been programmed[12]. A crucial element of the strategy is the integration of digital technologies into waste management systems. These include innovations like smart waste collection and AI-driven resource allocation tools, which are expected to improve operational efficiency, enhance transparency, and enable better tracking of waste materials throughout the cycle. Digital solutions are becoming increasingly important in modernizing waste management processes, ensuring that resources are used optimally and waste is minimized, which aligns with the principles of a circular economy (Maiurova et al., 2022).

The evolution of waste management in Italy has been significantly shaped by legislative interventions aimed at ensuring compliance with both national and European Union environmental standards. Central to this legal framework is the establishment of the *Registro Elettronico Nazionale per la*

[12] For more information: Economic Instruments for the Circular Economy in Italy, OECD. 2024.

Tracciabilità dei Rifiuti (RENTRI), introduced pursuant to Article 188-bis of Legislative Decree No. 152/2006 (*Codice dell'Ambiente*)[13]. RENTRI represents a key regulatory instrument designed to operationalize the principles of traceability, accountability, and transparency in waste management, as mandated by EU Directives on waste and the circular economy (notably Directive 2008/98/EC and its amendments)[14]. Its legal function is to standardize the obligations relating to waste documentation, including the digital issuance of transport identification forms and the maintenance of chronological waste registers, thereby replacing traditional paper-based compliance mechanisms[15]. The integration of RENTRI into the Italian legal system not only enhances administrative efficiency but also strengthens the enforcement capacity of environmental authorities by providing verifiable, centralized data on waste generation and movement[16]. As such, RENTRI constitutes a significant advancement in the implementation of environmental law in Italy, aligning national regulatory practice with the broader objectives of EU law and international environmental governance[17].

In accordance with Article 188-bis of Legislative Decree No. 152/2006, as amended by Legislative Decree No. 213/2022, specific categories of stakeholders are legally obligated to register with the National Electronic Register for Waste Traceability (RENTRI) via accreditation to the official telematic platform. These include entities and enterprises engaged in waste treatment, producers of hazardous waste, and those professionally involved in the collection, transport, brokerage, or trading of hazardous waste. Additionally, consortia established for the recovery and recycling of specific waste streams must comply with registration requirements. The obligation extends to certain actors handling non-hazardous waste as outlined in Article 189(3) of the same decree, including transporters,

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[13] Decreto Legislativo 3 aprile 2006, n. 152, *Norme in materia ambientale*, art. 188-bis, introdotto con modifiche dalla Legge 116/2014.

[14] Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives (Waste Framework Directive), and Directive (EU) 2018/851 amending Directive 2008/98/EC.

[15] Ministero dell'Ambiente e della Sicurezza Energetica, *RENTRI - Registro Elettronico Nazionale per la Tracciabilità dei Rifiuti*, Linee Guida operative (2023).

[16] ISPRA (Istituto Superiore per la Protezione e la Ricerca Ambientale), *Rapporto Rifiuti Speciali*, 2023, which highlights the expected benefits of RENTRI in terms of enforcement and monitoring.

[17] See European Commission, *EU Circular Economy Action Plan*, COM(2020) 98 final, which encourages Member States to adopt digital tools to improve waste tracking and reduce illegal dumping.

intermediaries, and producers of non-hazardous waste, provided they fall within the categories defined in Article 184 (points c, d, and g) and employ more than ten individuals. This regulatory framework aims to enhance traceability and accountability within the national waste management system, reinforcing both environmental protection objectives and compliance with European waste legislation.

Entities required to register with the National Electronic Register for Waste Traceability (RENTRI) must pay a registration fee of €10, which is due both at the time of registration and whenever company data is subsequently updated. Additionally, an annual contribution is required for each local unit at the time of registration, with the amount determined by the size and nature of the entity. Specifically, a €100 fee applies to initial waste producers with more than 50 employees, transporters, waste treatment operators, intermediaries, and consortia, including those identified under Article 18 of Ministerial Decree No. 59 of April 4, 2023. A reduced fee of €50 applies to producers with 11 to 50 employees, while a minimal fee of €15 is set for all other producers. In subsequent years, the annual fee must be paid by April 30 and is reduced to €60, €30, or €10 respectively, depending on the same criteria. This fee structure reflects a scaled approach aimed at ensuring proportional compliance while supporting the ongoing maintenance of the national waste traceability system.

3.4 The Challenges of Waste Cycle Management in Italy

Waste management in Italy is characterized by its fragmentation, which sets it apart from other network services that provide general economic interest (Agovino et al., 2017). This fragmentation stems from both the regional variability of legislation and the heterogeneous nature of production processes involved in the waste cycle. As such, different regions have different optimal scales for waste management services. Addressing this complexity requires stronger regulatory coordination at the national and regional levels, improved inter-municipal cooperation, and the widespread adoption of smart monitoring technologies to streamline operations (Mersico et al., 2025). By enhancing the efficiency of waste management operations, these technologies will help reduce inefficiencies and improve service delivery across Italy.

The upstream components of the waste cycle, including waste collection and sorting, are typically labor-intensive, lack economies of scale, and operate at smaller, more localized levels, usually at provincial or sub-provincial level. These sectors benefit from economies of density, where the cost of waste collection and sorting decreases with the concentration of population and waste generation (Carvalho et al, 2014). Due to their merit-good nature, these services are excluded from market competition and instead operate under allocation regimes defined by European and national regulations. These upstream services are essential but have limited capacity for large-scale efficiencies and thus are typically managed within local regulatory frameworks that account for the unique needs of smaller municipalities.

In contrast, the downstream components of the waste cycle, particularly waste treatment and disposal infrastructure, are capital-intensive and require significant investments (Tubertini et al., 2020). These systems tend to benefit from economies of scale, meaning that larger facilities and broader territorial areas result in more cost-effective operations. As a result, these downstream sectors are open to competition among service providers through regional authorization processes. This competitive environment promotes innovation, efficiency, and the adoption of the best practices in waste treatment and disposal technologies, ensuring that services are provided in a cost-effective manner across wider geographic areas (Di Foggia & Beccarello, 2021).

These structural differences in the waste cycle contribute to complex organizational and managerial frameworks, which can lead to diverse governance models (Citroni et al., 2009). Territorial areas responsible for waste management infrastructure and planning are often defined at the regional level, and while these regions typically manage large-scale operations, services such as waste collection, street sweeping, and transport tend to be smaller and operate at the provincial or sub-provincial levels. Consequently, the governance of these waste management sectors varies significantly from one region to another. Delays in defining service governance and the reluctance of local authorities to engage in collaborative governance structures have further complicated the situation, resulting in a fragmented governance landscape. In some regions, commissioners have been appointed to exercise substitute powers, helping to address this gap in governance.

Fragmentation is particularly evident in southern Italy, where single operator managed areas are less common. This results in a higher degree of organizational complexity and variability across regions, making it difficult to achieve a standardized and efficient delivery service (Beccarello et al., 2017). At the national level, urban waste management is organized into 76 optimal territorial areas (ATO), as mandated by regional regulations. In some regions, the concept of sub-ATO service areas has been introduced, increasing the total number of service areas to 243.

Italy's territorial characteristics are unique and contribute to disparities in infrastructure and public services. The historical urban-rural divide has created significant differences between metropolitan areas, which benefit from superior infrastructure and services (such as healthcare and education), and smaller municipalities and rural areas, which remain isolated from urban centers (Ambrosini et al., 2022). This divide poses significant challenges in terms of waste management, digital inclusion, and the overall efficiency of public service delivery. To address these issues, targeted policy interventions and strategic investments in sustainable infrastructure are required to ensure that rural and isolated areas are not left behind in the transition toward a more sustainable and inclusive waste management system.

These small municipalities play a pivotal role in the country's waste management strategy due to their large territorial coverage. They are predominantly located in regions where forming large urban clusters is challenging. These municipalities typically have concentrated settlements in valleys or dispersed populations in mid-hill and Apennine areas.

Over the past decade, land abandonment has been a growing concern in rural Italy, driven by the decline of the manufacturing sector, economic crises, and reductions in essential public services (Ambrosini et al., 2022). This trend has exacerbated population aging, undermined economic sustainability, and led to demographic decline, further diminishing the appeal of these rural areas.

The loss of economic opportunities and the reduction of services in these municipalities have made them less attractive places to live, contributing to the continued outmigration of younger generations. Despite these challenges, small municipalities are crucial for achieving the goals of the National Sustainable Development Strategy, as outlined by the National Agency for Territorial Cohesion. Strengthening rural policies has become a strategic priority, as these areas increasingly diversify their economies and provide new opportunities for residents. This diversification has been underway for years, even before the EU formally recognized it, as evidenced by the growing shift away from agriculture as the primary source of livelihood in these regions. Digital connectivity and the promotion of green energy initiatives are further enhancing the sustainability of these rural transformations, providing a foundation for long-term growth (Ambrosini et al., 2022).

Despite these challenges, there are significant opportunities to leverage the territorial capital of small municipalities and rural areas. Two waste management initiatives are presented in the following paragraph.

3.5 Local government initiatives: The case of Castigliole delle Lanze, Dogliani and Peccioli

While many regions in northern Italy demonstrate strong performance in this area, central and southern parts of the country continue to exhibit significant deficiencies in effective waste handling (Musella, 2019). Understanding the classification of waste is foundational to any analysis of waste management policy. Italian regulations divide waste into three categories: (i) special, (ii) urban, and (iii) hazardous. Special waste originates from sectors such as agriculture, construction, demolition, mining, industrial and commercial activity, as well as healthcare and obsolete machinery. Urban waste includes household waste, non-hazardous waste from other sources (when similar in nature and quantity to household waste), and waste from street cleaning and cemetery maintenance. Hazardous waste is generated from industrial processes that involve toxic substances (Osservatorio Nazionale Rifiuti, 2007). These categories are subject to increasingly complex legislation and escalating disposal costs. However, comprehensive data are predominantly available only for urban waste, with industrial waste often underreported (Interview with A. Cavaliere, President of the Osservatorio Nazionale Rifiuti, 8 October 2008).

Italian law mandates regional self-sufficiency in managing municipal solid waste (MSW), while non-municipal waste may be transferred freely to optimize recovery and disposal (OECD, 2024). An MSW management system begins with sorting and collection, followed by transportation, recovery, and final treatment or disposal (Jannsson, 2015; Cohen, 2021). In developed countries, regional waste systems increasingly utilize large-scale anaerobic digestion and central composting plants, covering both urban and rural areas (Mihai, 2017). In Italy, the dominant forms of separate waste collection include door-to-door systems, centralized bring points, or integrated models combining both. Among these, the door-to-door model has proven the most effective in increasing the quantity and quality of recyclables. It also significantly reduces greenhouse gas emissions associated with MSW, particularly when combined with best available technologies (Calabrò, 2009). However, many municipalities still rely on outdated infrastructure, hindering environmental performance (Musella, 2019). While door-to-door systems improve recycling rates, they do not guarantee a reduction in overall waste generation (Bonelli, 2016). More effective are Pay-As-You-Throw (PAYT) systems, which have demonstrated clear results in reducing waste volumes. For example, municipalities like Castagnole delle Lanze and Dogliani have implemented pre-paid bag schemes with notable success, while Cambiano has adopted a transponder-based collection model. These municipalities also invest in targeted communication campaigns and promote home composting, which has shown strong results in rural areas (Bonelli, 2016).

Recycling is not just a technical challenge but also a social, environmental, and economic one, often driven by public pressure (Cohen, 2021). In Italy, biological treatment of municipal waste is carried out through composting (aerobic digestion), anaerobic digestion (AD), and integrated plants that combine both processes. A prime example of innovation in local waste management is the *Peccioli System*. Established in 1997 through the formation of the joint-stock company Belvedere, owned 64%

by the municipality and 36% by local citizens, it manages a landfill in the village of Legoli. The facility receives unsorted municipal waste from six municipalities and processes it through a mechanical-biological treatment plant. This separates waste into an organic undersieve (used for biogas production) and a dry oversieve (sent to landfill), while recovering recyclable metals. The biogas plant generates over 13 million kWh of electricity annually, complemented by a 1,000 kWp solar photovoltaic system that feeds an additional 1 million kWh into the national grid.

Peccioli stands out for reinvesting the economic gains from waste management into cultural, social, and environmental projects. Urban gardens are made available free of charge to residents, and the landfill itself has been artistically transformed with murals by Sergio Staino and David Tremlett, turning it into an open-air amphitheater for public events. Since 2004, these initiatives have been institutionalized through the Peccioli Foundation, which serves as a hub for artistic, technological, and social experimentation. The town even pioneered the use of service robots for cleaning, grocery delivery, and elderly assistance. This strategic focus on the circular economy has become central to Peccioli's development policies, demonstrating how household waste can be transformed into a vehicle for social cohesion, economic opportunity, and cultural revitalization. Peccioli's example embodies a resilient community model committed to ecological transition, digital innovation, and inclusive development.

Municipal governments are in charge of the provision of waste management services for their local communities; however, their choices on waste management have consequences that are seldom limited to their administrative borders, for instance because part of the waste generated by their local community is transferred and processed somewhere else. Moreover, local governments are in a position to set incentives for their citizens to improve waste management e.g. by pushing better waste separation at household level, or sanctioning illegal waste disposal (D'Amato et al., 2018; Marques et al., 2018; Sastre et al., 2018).

3.6 Socio-Economic Factors Influencing Waste Management

Geographic/demographic variables are commonly used in the literature as factors that potentially may affect waste management and its costs. A first potential factor that may affects the SCR is the overall surface area, which refers to the square kilometers of the entire municipality. If the area increases, the collection costs decrease through the presence of economies of scale (Domberger et al., 1986, Simoes et al, 2012); however, lager areas my increase the cost due to the service inefficiency (Stevens, 1978; Callan and Thomas 2006).

Socio-economic factors highlight how the value added per capita is one of the main factors that characterize the Northern Italian area. Empirical studies argue that separate collection is positively correlated to the prosperity of a region. Thus, in areas with weaker economies, as those in Southern Italy, good performances of waste management may be complicated. The use of waste management methods less performing could be compensated by persuading people to differentiate, by leveraging on their intrinsic motivation and pro-environmental behaviour (Musella et al., 2019).

According to ISPRA (2023) The management of municipal solid waste in the referenced context reveals a diversified treatment approach, with varying methods contributing to the overall waste processing system. The most prominent strategy is material recovery, which accounts for 29% of the total waste treatment, reflecting a strong emphasis on recycling and the reintegration of secondary raw materials into the production cycle. Biological treatment of the organic fraction from separate collection (RD) follows closely at 24%, highlighting the importance of organic waste valorization, particularly through composting and anaerobic digestion. Incineration represents 19% of the treatment share, serving as a major energy recovery pathway, while landfilling still comprises a significant 16%. This is particularly concerning, as landfilling is highly polluting, contributing to soil contamination, methane emissions, and long-term environmental degradation. Intermediate treatments such as selection and/or biostabilization represent 4%, preparing waste for subsequent recovery or disposal phases. Exported waste constitutes 5%, often due to capacity or regulatory limitations at the national level. Smaller shares are attributed to co-incineration (1%), domestic composting (1%), and landfill cover usage (1%), reflecting specialized or localized practices within the broader system. Together, these figures illustrate a mixed strategy that leans toward circularity while still relying substantially on thermal and landfill options.

3.7 Innovative Waste Management Practices

The inevitable generation of waste materials necessitates the development of comprehensive and efficient Waste Management Systems (WMS), requiring strategic planning by both governmental and non-governmental actors (Nayeri et al., 2025). In innovation-driven countries, heightened public awareness and education around environmental issues contribute to stronger societal engagement with recycling and sustainability initiatives. Innovation not only fosters a cultural shift toward environmental responsibility but also introduces advanced solutions that simplify and enhance individual participation in recycling efforts. The societal adoption of green technologies typically evolves alongside broader technological advancements (Laureti et al., 2024). Recent studies have introduced the WM5.0 framework, an innovative approach integrating principles of the Fifth Industrial Revolution, which emphasizes sustainability, digitalization, human-centricity, and resilience. Within this model, decision-making is guided by indicators such as the 5Rs (Refuse, Reduce, Reuse, Repurpose, Recycle), reliability, operational feasibility, safety, investment costs, and flexibility (Nayeri et al., 2025).

Regulatory evolution has paralleled technological advancement, with increasing demands for precise, real-time monitoring of waste generation and processing. This is crucial to ensure consistency in measuring the extent to which packaging waste is effectively recycled into new products. A pivotal development in this domain is the adoption of the National Electronic Register for Waste Traceability (RENTRI), which was formalized through Ministerial Decree No. 59 on April 4, 2023, pursuant to Articles 190 and 193 of Legislative Decree No. 152/2006, and published in the Official Gazette on

May 31, 2023. RENTRI establishes new digital templates for the chronological waste load/unload register and the waste identification form, with deadlines for registration and implementation delineated in Articles 13, 9, 4, and 7 of the regulation. To support compliance, the Directorate Decree of September 21, 2023, provides standardized procedures and timelines. RENTRI's digital infrastructure facilitates traceability, streamlining documentation and enabling regulatory authorities to combat illegal waste management practices while improving operational clarity for businesses (OECD, 2024).

In parallel, technological innovation continues to reshape waste management approaches across diverse geographic contexts. Urban and rural areas require distinct technical and social innovations to manage solid waste effectively (Bolton, 2016). In rural regions, four cornerstone technologies—animal fodder processing, briquetting, anaerobic digestion (biogas), and composting—are particularly suited for managing agricultural and organic municipal waste (El-Haggar et al., 2007). The waste management industry is also experiencing a paradigm shift from traditional models focused solely on transportation and treatment toward integrated systems emphasizing sustainable service provision and material recovery (Aid et al., 2017). To support this transformation, many organizations are embracing inter-organizational frameworks such as the circular economy and industrial symbiosis to collaboratively generate value with stakeholders (Aid et al., 2017; Singh et al., 2014). However, the sector remains challenged by a tendency to isolate waste from broader value chains.

Effective governance plays a crucial role in enabling these innovations. According to the OECD (2024), a multi-tiered governance framework is essential to institutionalize circular economy practices. This framework should function vertically linking national, regional, and municipal governments and horizontally encouraging cooperation among local jurisdictions. Capacity-building at the sub-national level is particularly important to ensure policy coherence and effectiveness. Instruments supporting multi-level governance already exist, including the "Tavolo interistituzionale per il Piano della Gestione dei Rifiuti," which coordinates the development of the National Waste Management Plan with stakeholders such as regional governments, ISPRA, ANCI, MIMIT, and

ARERA. Further, in October 2022, the Ministry of the Environment and Energy Security (MASE) established an observatory to oversee implementation of the National Strategy for the Circular Economy (MiTE, 2022).

3.8 Final considerations

Effective waste management in rural areas remains a significant challenge due to geographic dispersion, limited infrastructure, and often lower institutional capacities. While many small municipalities have adopted promising practices such as door-to-door collection, home composting, and PAYT schemes these efforts are often fragmented and lack systemic coordination. One critical gap is the absence of robust traceability systems capable of monitoring the flow of waste from collection through to treatment and final disposal.

Introducing digital traceability tools, such as those already piloted in larger municipalities and supported by national systems like RENTRI, is essential for improving accountability and performance in rural waste management. These systems can provide real-time data, enhance regulatory oversight, and help local administrations make evidence-based decisions tailored to their specific needs. Moreover, they support the prevention of illegal dumping and increase transparency in waste treatment operations. However, despite their potential, there is currently no comprehensive study evaluating the environmental and economic impacts of such traceability systems, particularly in the context of small rural municipalities. This lack of assessment limits the ability to measure their cost-effectiveness or their contribution to broader sustainability goals.

For rural areas to align with national circular economy objectives and EU directives, investing in scalable, user-friendly traceability infrastructure is no longer optional. Future research should prioritize evaluating the systemic benefits and limitations of these tools, in order to inform equitable, evidence-based waste policy across all regions. In order for the choices of the decision-makers to be facilitated with regard to their objectives and performance, several types of methods can be used i.e. for the analysis of the environmental, economic, and social aspects of waste management process. Waste management disposal chain is a complex system involving many stakeholders. Waste management's disposal chain is a complex system involving many stakeholders.

Typical waste transfers involve citizens and industries; municipalities; outsourced entities that collect and manage the bins; different centers that deal with collection, disposal, and recycling; and producers of recycled waste materials that put new products on the market (Baralla et al., 2023).

The monitoring and recording of waste collection data plays a crucial role in ensuring compliance with applicable laws and regulations. It also has the potential to provide valuable insights that could influence future legislation and ultimately prevent the inefficient disposal of waste through methods such as landfilling or incineration. However, the process of tracking waste and monitoring ownership to generate these important data are inherently complicated (Offenhuber et al., 2023). Challenges can arise from a variety of sources, such as products breaking down into smaller components, existing laws such as extended producer responsibility, which requires manufacturers to dispose of the subsequent waste from their products, and the problem of the abandonment of ownership through littering or dumping. Tracking waste and monitoring its owners currently requires more pragmatic solutions than those currently in widespread use. (Steenmans et al., 2020).

Chapter 4. Methodology

This chapter outlines the methodological approach adopted for this study, which investigates blockchain technology's environmental and economic impact on waste management in Italian rural areas.

Methodology refers to how the researcher practically finds out whatever he or she believes can be known (Howell, 2012). To carry out valid research a research strategy has to be adopted designing the guidelines that show how the research is to be conducted (Sarantakos, 2005).

The purpose of this chapter is to detail the research design and justify the methodological choices made in alignment with the study's objectives. Section 4.1. begins with a discussion of the case study approach and the rationale for selecting a single case. Section 4.2. describes the procedures for case selection, data collection, and data analysis. Section 4.3. Presents the considerations regarding ethical conduct, and potential methodological limitations are also addressed.

4.1 Research Design

This paragraph aims at presenting the research design that will serve as a foundation for the study. A crucial choice in the research design process is selecting the research approach, as it dictates the methods through which pertinent information for the study will be gathered; nonetheless, the research design process encompasses numerous interconnected decisions (Miller et al., 2002; Sileyew et al., 2019).

For this study a single case study design was chosen to provide an in-depth understanding of the case or phenomenon being studied within its real-life context (Gaya et al., 2016). This approach is particularly well-suited to exploring complex organizational, phenomena where boundaries between the phenomenon and its environment are not clearly defined (Tsang et al., 2013). Additionally, to estimate the environmental impact of blockchain technology, the SOPA methodology has been implemented.

The background of the methodological structure of this study is based on the three philosophical stances, which, according to Terre Blanche and Durrheim (1999) are the foundational assumptions that guide the research process which include beliefs about the nature of reality (ontology[18]), what constitutes valid knowledge and how it is acquired (epistemology[19]), and the values and aims that inform research (axiology). Understanding these assumptions is critical for constructing a coherent

[18] The term Ontology is based on two Greek words: onto, which means "being" and logia, which means "science, study or theory". Ontology refers to a branch of philosophy concerned with articulating the nature and structure of the world (Wand and Weber, 1993, p. 220).

[19] Epistemology poses the following question: What is the relationship between the researcher and what is known?

and meaningful research framework. Additionally, the philosophical stances shape the way researchers engage with theory and reasoning (Rouse et al., 2018).

Furthermore, according to (Kumar et al., 2018) theories are "the analysis and statement of how and why a set of facts relates to each other". Approaches to theory involve mental operations that bring order to data and connect it to broader conceptual frameworks. A solid grasp of the underlying research paradigm is therefore essential for generating meaningful interpretations and ensuring that knowledge production is consistent and credible (Elgeddawy et al., 2024).

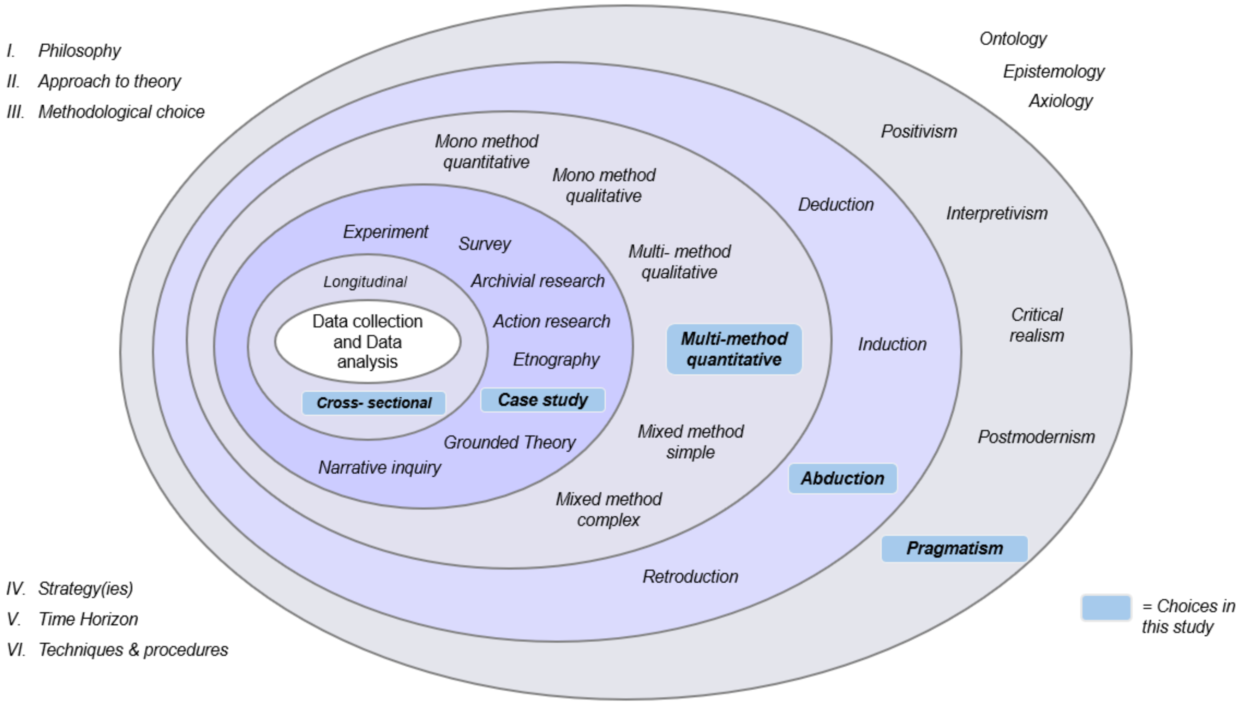
Within this context, pragmatism emerges as a suitable stance for this study. Pragmatism developed in the late 19^{th} and early 20^{th} century as a philosophical movement that focused on the practical consequences of social reality. It allows for flexibility and encourages the use of both qualitative and quantitative methods under appropriate conditions, aiming for solutions that are both theoretically informed and practically useful (Iosifides et al., 2012; Maxwell et al., 2010).

A prominent theme in the literature on pragmatism is that it does not dictate choice on methods (Feilzer et al., 2010; Teddlie et al., 2010). It supports methodological pluralism, providing a framework for that enables researchers to choose which method is more appropriate and combine approaches to gain a more comprehensive understanding of the problem under investigation (Kaushik et al., 2019). Pragmatic research thus prioritizes practical implications and real-world impact, acknowledging that all knowledge creation is a social practice with tangible consequences (Feilzer et al., 2010). This knowledge is not static; rather, it is dynamic, evolving, and oriented toward practical consequences (Kelly et al., 2020). Pragmatism holds that the value and meaning of options and “facts” captured in research data that are assessed through examination of their practical consequences (Dewey, 1938). The pragmatism epistemological approach helps validate research questions and focus inquiry processes. Furthermore, the embeddedness of inquiry in practical, everyday situations makes classical pragmatism relevant to theoreticians and practitioners addressing the helps a key challenge in organizational research developing a “mediated” understanding of complex organizational processes (Lorino et al., 2018).

Founding its philosophical stance on pragmatism, this research adopts an abductive form of logical reasoning. Such approach allows researchers to engage with real-world issues beginning with an area of concern grounded in practical observations or preliminary data. To pinpoint a pertinent research question, conduct thorough and methodical research (Van Maanen et al., 2007), the process of abduction begins with the area of concern (A), informed by data regarding the phenomenon, which can be obtained through observing a practical issue (Kovács & Spens, 2005) or through an exploratory pre-study (e.g. Wilson, 2013). Typically, researchers rely on existing theoretical knowledge and experience (e.g. via literature reviews) since this shape their perception of the real world (Dubois et al. 2002). From the insights gained through the initial real-world observation, a preliminary theoretical or conceptual framework (F) is formulated, comprising preconceptions or initial efforts to align theory with practice. This framework serves as a reference point for re-engaging with the empirical realm, guiding the search for data. The objective is to harmonize theory and reality in order to address a practical issue by systematically integrating empirical data with theoretical insights (Storbacka, 2011). Throughout this method-driven interaction (M), the framework is gradually adjusted or refined over time based on findings from fieldwork (i.e. validation) as well as through analysis and interpretation (Dubois et al., 2002). The ongoing 'back and forth' dialogue between theory and practice occurs repeatedly until theory aligns with reality, thus achieving a systematic integration (Dubois et al., 2014).

Third, methodology refers to the systematic application of the research stance and reasoning modes to the study (Castles et al., 2012). It acts as a bridge between abstract philosophical assumptions and concrete research procedures. The choice of the specific techniques for data collection and analysis, is guided by this methodological foundation. The case study-based research strategy is usually founded in qualitative research methods where the researcher explores an activity, a process or an event using data collection procedures over a sustained period of time (Stake, 1995). However, this study is using multi-method research where the case study is the first step to explore the process of interest in the first stage of the research. In the second stage a quantitative method is applied to analyse the data collected from primary and secondary sources.

Table 5 - Research Methodology

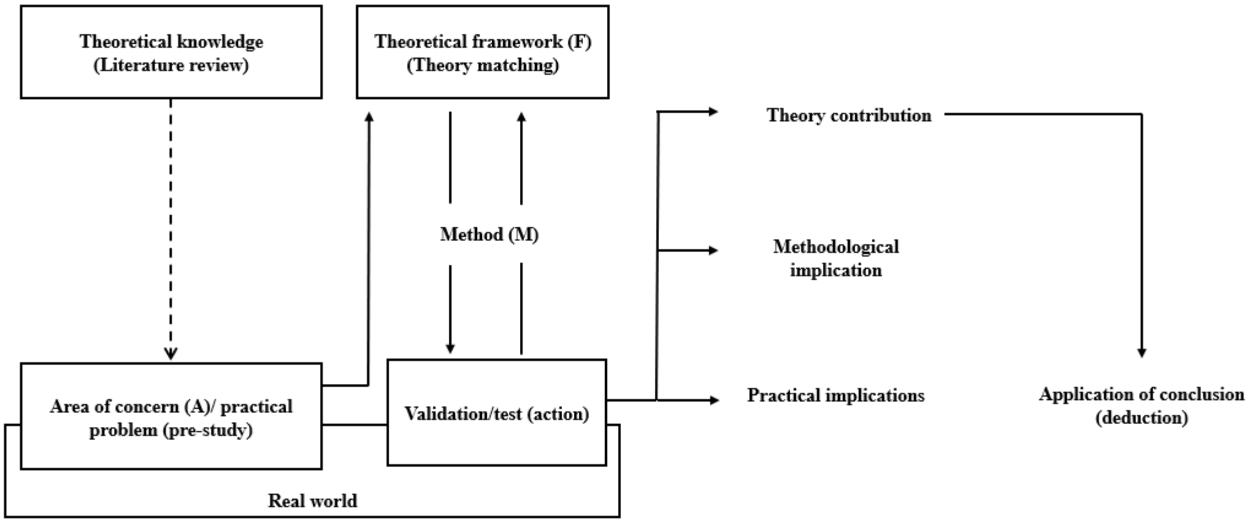


Source: Own elaboration, adaptation of (Saunders, 2003).

Having established the philosophical stance, theoretical orientation, and methodological framework, the next section discusses the specific choices made for the research design and methods employed in this study.

Finally, this study, a cross-sectional study has been selected as the core research strategy. This approach is appropriate for addressing the research aims, as it allows for in-depth analysis of a specific context at a particular point in time. The use of cross-sectional data contributes to theory development, helps minimize research bias, and enhances the generalizability of the findings (Lillis, 2005).

Table 6 - Conceptual overview of abductive approach

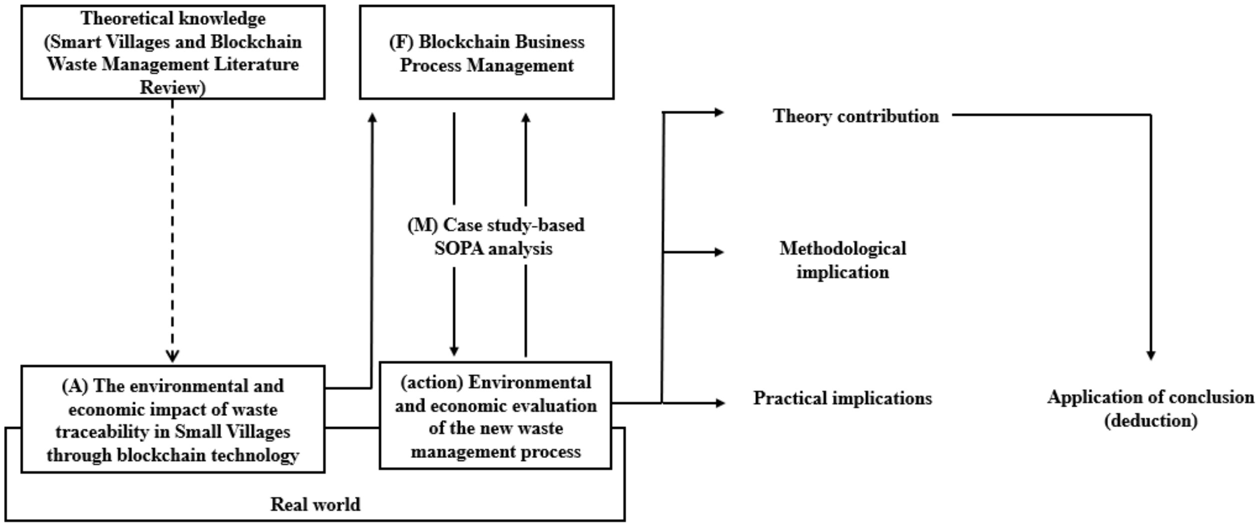


Source: Adaptation from Helecker, 2015 based on Kovács, 2005.

4.2 Data collection and analysis methods

The diagram presents the study's research framework. It begins with a literature review on Smart Villages and blockchain waste management, forming the theoretical foundation of knowledge. This knowledge informs a real-world investigation into the environmental and economic impacts of implementing blockchain for waste traceability (A). The practical evaluation of this new process is supported by Blockchain Business Process Management Theory (F). Finally, a case study-based SOPA analysis (M), serve as key methodological tool. The findings contribute to theory, methodology, and practice, generating insights that are then applied deductively to inform future strategies and policies.

Table 7 - Conceptual Overview of Abductive Approach Adapted To Blockchain Waste Management Research



Source: Own elaboration adapted from Helecker, 2015.

4.3 Blockchain Architecture and Design

Firstly, there is a need to understand that, although many organizations are looking at blockchain technologies, this solution is not always appropriate (Pedersen et al., 2019). Furthermore, determining what kind of blockchain and which configuration to use has thus far presented a major obstacle for decision makers and system architects (Pedersen et al., 2019). Existing works in literature on BCT and BPM were mostly on the fulfilment of the functionalities of traditional BPM tools (Meironke, 2019). To understand what blockchain architecture a suitable solution for waste management would be, the ten-step blockchain decision path has been applied.

It is important to remember that a blockchain can be described as a shared database, in spite of all the various fields of application cited earlier. Therefore, the evaluation of the suitability of a blockchain approach, begins with the understanding whether information storage is essential for the service, then assessing if conventional database systems can be implemented and used for the task. If they can, it's more practical to rely on proven technologies rather than implementing blockchain for data handling and transaction processing.

In the case of waste management, the frequent need to exchange data among a chain of parties indicate a need for a database, The data is owned by different organizations and the environmentally friendly prosecution of the end-of-life supply chain depends on the exchange of information. Organizations should also consider the scalability issues relating to the amount of data that needs to be stored. Storing and exchanging a lot of data can be slow and expensive due to the prolonged periods and transaction fees.

Secondly, the choice of the right blockchain platform upholds to the decentralized transactional database or an essential blockchain functionality. Furthermore, the number of contributors to the blockchain needs to be defined. Only if the engagement of contributors involves multiple parties, the blockchain system becomes an efficient service. In the waste management case there are multiple parties involved. This includes waste producers, collection agencies, recycling facilities, regulatory authorities, and sometimes even consumers. Each of these stakeholders contributes data at various stages of the waste lifecycle, from generation and transportation to treatment and final disposal.

The adoption of blockchain technology in waste management systems necessitates a critical evaluation of its contextual appropriateness, particularly in decentralized and rural environments. While the discourse surrounding blockchain has expanded considerably in recent years, its practical applicability is not universal (Pedersen et al., 2019). One of the most persistent challenges facing decision-makers and system architects is determining the suitability of blockchain over conventional alternatives, as well as identifying the optimal configuration and platform for specific use cases (Pedersen et al., 2019). In response, this research applies the ten-step blockchain decision path, which offers a structured methodological approach to assess whether BCT provides substantive value in comparison to traditional information systems.

The initial consideration is whether information storage is essential to the service. In the context of waste management, data pertaining to the classification, origin, quantity, and movement of waste must be recorded and shared across multiple stakeholders. This evidences the need for a shared data infrastructure. The subsequent question, “can conventional database systems adequately fulfill these needs?" highlights that while relational databases can manage centralized records, they typically lack the transparency, tamper-resistance, and decentralized control required in multi-actor, compliance-sensitive domains such as waste governance.

A pivotal inquiry concerns whether multiple parties are involved. Waste management involves a distributed network of actors, including waste producers, collectors, transporters, recycling facilities, and regulatory agencies. Each contributes and requires access to data throughout the waste lifecycle. This leads to the question: "do these actors have conflicting interests or lack mutual trust?" In many real-world scenarios, discrepancies in reporting, attempts to circumvent regulations, and data manipulation risks reveal the existence of misaligned incentives and a lack of trust. In such contexts, blockchain's decentralized architecture and immutability enable the construction of a trustless environment wherein data validity is guaranteed algorithmically rather than through institutional trust.

The next evaluative step is to consider whether participants seek to avoid reliance on a trusted third party. In most national and cross-border waste management systems, there is currently no centralized authority that serves as a neutral data integrator across all stages and actors. Blockchain offers a decentralized alternative, enabling peer-to-peer transactions and direct data validation without requiring a central intermediary. Furthermore, the question arises: "do the rules governing system access differ between participants?" Waste management actors require differentiated access privileges. For instance, regulators may require full data visibility, while private collectors or processors may need access limited to their operational scope. Blockchain platforms, particularly permissioned ledgers, support such granularity through smart contracts, which can assign and enforce distinct roles and permissions.

It is also crucial to assess whether the rules for transacting remain largely unchanged. Since blockchain protocols, and especially smart contracts, are not easily modified post-deployment due to consensus constraints, the technology is best suited to environments with relatively stable regulatory frameworks. In this regard, the waste sector, particularly in compliance-driven systems such as Italy's

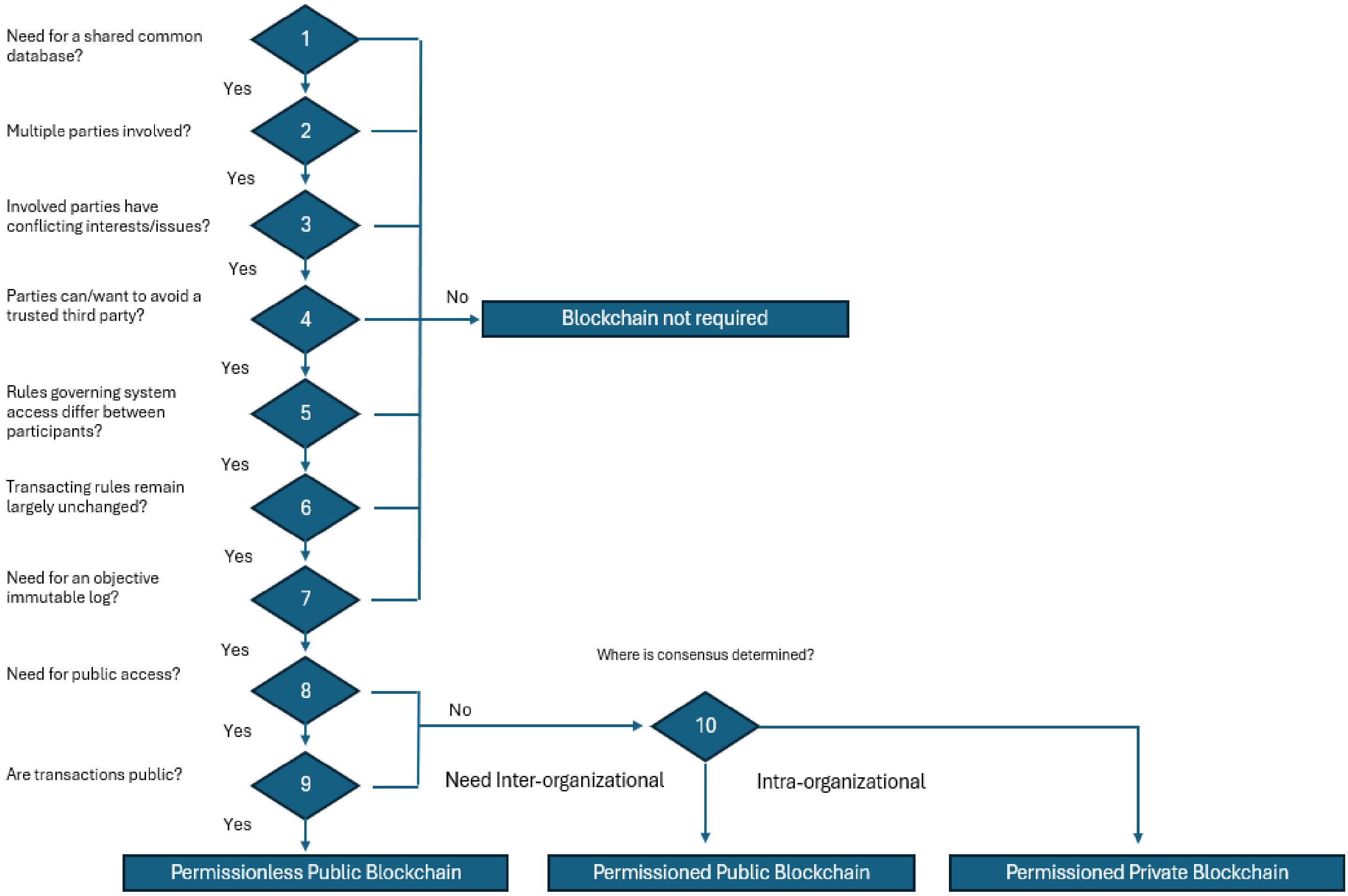
RENTRI registry, is characterized by routine and standardized data reporting, making it compatible with blockchain's architectural rigidity.

An additional determinant of suitability is whether there is a need for an objective, immutable log. Blockchain inherently provides an incorruptible, time-stamped record of all transactions, which is highly valuable for auditing, legal verification, and regulatory transparency. Traditional paper-based or centralized digital records often lack this level of integrity and traceability.

The final considerations pertain to data privacy and public accessibility. The questions "is public access required?" and "are transactions public?" guide the choice between permissioned and permissionless blockchain architectures. In waste management applications, particularly those handling commercially sensitive or personal information, full public access is generally undesirable. Therefore, permissioned blockchains are more appropriate, allowing only authenticated stakeholders to read or write data. This is consistent with systems like RENTRI, where access to detailed waste records is limited to authorized entities, while aggregated data may be made available for policy or educational purposes. Such a controlled transparency approach balances regulatory compliance, operational confidentiality, and public accountability.

In summary, by applying the ten-step blockchain decision path and systematically addressing each critical decision-making criterion, this research establishes that blockchain while not universally applicable can be appropriately tailored to meet the specific requirements of waste management systems. In multi-actor, low-trust environments characterized by complex compliance obligations, blockchain provides a viable and robust infrastructure for enhancing data integrity, transparency, and operational coordination. This methodological framework supports evidence-based adoption of BCT, avoiding the pitfalls of technocentric implementation and grounding innovation in empirical and regulatory realities.

Figure 1 - New technology application, decision making process



Source: Based on Pedersen et al. 2019

4.4 SOPA methodology

SOPA proposes a three-step approach for analyzing business processes for their environmental impact and their sustainability-oriented re-design. SOPA is a framework for sustainability-oriented process analysis, that combines Life Cycle Assessment (LCA) and activity-based costing (ABC) within BPM life cycle. The aim is to assess the environmental impact of individual activities, and hence, a holistic approach to process assessment and re-design. The following section presents background information on ABS, LCA and BPM and business process simulation. Then the SOPA method, used in this work, is detailed.

Unlike the environmental dimension of sustainability assessment methods, the economic and social indicators and evaluation methods still need scientific progress. The life cycle perspective is inevitable for all sustainability dimensions in order to achieve reliable and robust results. LCSA is intended to have a tangible effect on the sustainable development of society.

LCA is an analytic environmental management tool that follows the ISO 14040 and 14044 standards. Specifically, according to ISO 14040 LCA is defined as "compilation and evaluation of the inputs, outputs and the potential environmental impact of a product system throughout its lifecycle".

4.4.1 Life Cycle Assessment (LCA) in Environmental Impact Assessment

Life Cycle Assessment (LCA) is a comprehensive and structured approach within the broader field of Environmental Impact Assessment (EIA) that is designed to evaluate the environmental impacts associated with a product, service, or system throughout its entire life cycle. The methodology recognizes that sustainability encompasses not only the financial and economic costs but also a variety of environmental burdens, including but not limited to emissions, energy use, and waste generation. As noted by Glasson and Therivel (2019), Environmental Impact Assessment (EIA) serves as a systematic framework for identifying, predicting, assessing, and mitigating the environmental, social, and other impacts of development proposals.

The significance of LCA lies in its capacity to consider the environmental effects at each stage of a product's life, from raw material extraction, through manufacturing and use, to eventual disposal. The methodology is governed by the ISO 14040 and ISO 14044 standards (ISO, 2006), which provide a structured approach for measuring and assessing the environmental impact across the entire life cycle of products or services, ensuring comprehensive and reliable sustainability assessments.

LCA is divided into four distinct and critical phases, each of which plays a vital role in ensuring a thorough and accurate sustainability analysis. The first phase, goal and scope definition, is foundational to the study. This phase establishes the purpose of the assessment and outlines its boundaries, setting the stage for a focused and meaningful analysis. The definition of the goal ensures that the assessment is aligned with the research objectives, yielding results that are relevant to decision-making in sustainability management. LCA can address various types of research and policy-related inquiries. These may include predictive scenarios, which assess how a system will behave under specific conditions, exploratory scenarios, which explore potential system behaviors under various assumptions, and normative scenarios, which aim to identify pathways to achieve specific environmental objectives or sustainability targets (Finnveden, 2009). The scope of the analysis goes beyond goal definition by involving the determination of the functional unit, which quantifies the performance of a product system and allows comparisons between different alternatives. For instance, a functional unit might specify the amount of product required to meet a specific performance level or service. In addition to this, system boundaries need to be carefully defined to determine which processes, stages, and impacts are included or excluded from the analysis, ensuring consistency and relevance across the study.

The second phase, life cycle inventory analysis (LCI), is an essential component of LCA that focuses on data collection. This phase involves gathering and quantifying all the necessary inputs such as raw materials, energy consumption, and water use, as well as outputs, which include emissions, waste, and by-products, associated with each stage of a product's life cycle. LCI is a data-intensive and labor-intensive process, often requiring considerable time and effort to compile accurate data. The collected data is typically expressed in various units, such as kilograms of carbon dioxide emissions, cubic meters of natural gas consumption, or milligrams of specific chemical pollutants (De Brujin et al., 2002). Given the complexity of data collection and the wide variety of materials, processes, and regions involved, numerous national, regional, and industry-specific databases have been developed to support LCA practitioners in streamlining the process. These databases contain standardized datasets for commonly used materials and processes, such as electricity generation, transportation, and raw material extraction. One of the most widely utilized and trusted databases is the *Swiss ecoinvent* database, which integrates seamlessly into multiple LCA software tools. The *ecoinvent* database offers high-quality, peer-reviewed inventory data, significantly enhancing the reliability, consistency, and comparability of LCA studies while easing the data-gathering workload for analysts (Wernet et al., 2016; Finnveden et al., 2009).

The third phase of LCA, life cycle impact assessment (LCIA), takes the data generated in the inventory phase and translates it into environmental impact indicators, providing a comprehensive understanding of the potential environmental consequences of a product or process. The impact assessment phase involves selecting relevant impact categories, which typically include climate change, ozone layer depletion, eutrophication, acidification, human toxicity, and ecotoxicity, among others. It also applies characterization models that establish relationships between inventory data and environmental impacts, for example, quantifying how a given amount of carbon dioxide emissions contributes to global warming or how particulate matter affects human health. To further contextualize the impact, normalization techniques may be applied to express the impact scores relative to a reference system, such as the average environmental impact per person, per country, or per region. Weighting techniques may also be used to aggregate different impact categories into a single composite score, which simplifies the decision-making process by reducing complexity and offering a consolidated view of the environmental consequences. The LCA phase is critical because it helps translate raw inventory data into actionable insights, identifying which life cycle stages or processes contribute most significantly to environmental impacts, allowing stakeholders to pinpoint areas for improvement.

The final phase, life cycle interpretation, is the culmination of the LCA process and involves synthesizing the results of the entire assessment. During this phase, analysts critically evaluate the assumptions and methodological choices made throughout the study, ensuring transparency and scientific rigor. This phase is crucial for deriving meaningful conclusions from the study and providing actionable recommendations for decision-makers. The interpretation process involves identifying key issues by analyzing the contributions of different life cycle stages to the overall environmental impact and performing sensitivity and uncertainty analyses to evaluate the reliability and robustness of the results. By doing so, the interpretation phase allows for the identification of the most significant environmental hotspots across the life cycle. Based on these insights, recommendations for enhancing sustainability performance are formulated. These might include suggestions for improving product designs, optimizing supply chains, or selecting alternative materials that have a lower environmental footprint, thereby supporting organizations in making more environmentally responsible decisions.

LCA is widely recognized as a powerful tool for measuring and understanding the holistic environmental impact of products, services, and systems. Its ability to quantify environmental burdens across an entire life cycle enables businesses, policymakers, and researchers to make data-driven, evidence-based decisions that contribute to sustainability (Santos et al., 2021). The structured methodology of LCA ensures consistency and comparability, making it an invaluable tool for assessing the environmental implications of a wide range of human activities, from manufacturing and energy production to consumption and disposal. As a result, LCA provides the critical insights needed to support sustainable development goals, influence policy-making, and guide corporate social responsibility strategies (Almusaed et al., 2024).

In conclusion, Life Cycle Assessment plays an essential role in environmental impact evaluation by providing a standardized, systematic approach for evaluating sustainability. The four-phase methodology, goal and scope definition, inventory analysis, impact assessment, and interpretation offers a comprehensive framework for understanding, quantifying, and reducing environmental impacts. The use of extensive databases and advanced computational tools further enhances the accuracy, applicability, and scalability of LCA studies. As environmental sustainability becomes an increasingly pressing global issue, the adoption and application of LCA are expected to grow, influencing the development of more responsible policies, technologies, and business practices. The continued advancement of LCA techniques, alongside improvements in data availability and computational power, promises to make this method even more integral to sustainable decision-making in the years to come.

Several approaches are suitable for the evaluation of the economic dimension of sustainability which is usually done by considering the business perspective and the customer's perspective. From the business standpoint the manufacturing costs are considered, while from the customer perspective the lifecycle costs[20] are estimated.

Furthermore, "environmental life cycle costing" is "an assessment of all costs associated with the life cycle of a product that are directly covered by any one or more of the actors in the product life cycle with complementary inclusion of externalities that are anticipated to be internalized in the decision-relevant future" (p. 173).

The effects of the organization on stakeholders at local, national and global levels are used to evaluate the social dimension of sustainability captures the impact of an organization, product or process on society. However, the selection of social criteria and their quantification is one of the major challenges when implementing the concept of sustainability. There are still research needs and consensus needs of the involved stakeholders and no uniform usage of a standardized set of indicators[21].

Life Cycle Sustainability Assessment Evaluation Schemes[22].

4.4.2 An overview of Activity-based costing (ABC)

Activity-based costing (ABC) is a cost allocation method that acknowledges all activities within an organization, whether direct or indirect, as essential contributors to the overall business goals. These activities should be considered when distributing costs (Goebel et al., 1998). Unlike traditional

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[20] The lifecycle costs are the total costs o a system or a product, produced over a defined lifetime. If the assessment or design (planning, accumulation and control is limited to actual cost, one can refer to it as life cycle costing in a narrow sense. Including further performance parameters can be addressed by life cycle costing in a broader sense.

[21] Extensive research on sustainability indicators with focus on the social dimension produced 150 different social indicators and objectives. Finkbeiner, M.; Günzel, U. Analyse von Methoden zur sozialen Produktbewertung und Verwendbarkeit im Kontext von Ökobilanzen; DaimlerChrysler AG: Stuttgart, Germany, 2005.

[22] The Eyerer group addressed the three dimensions technology, economis and ecology. Eyerer, P. Ganzheitliche Bilanzierung, Werkzeug zum Planen und Wirtschaften in Kreisläufen; Springer: Heidelberg, Switzerland, 1996.

19. Finkbeiner, M.; Saur, K. Ganzheitliche Bewertung in der Praxis. In Ökologische Bewertung von Produkten, Betrieben und Branchen; Symposium Bundesministerium für Umwelt, Jugend und Familie Österreich: Vienna, Austria, 1999.

costing systems, which often allocate costs based on broad and simplistic measures such as direct labor hours or machine hours, ABC takes a more precise approach by identifying the specific activities that generate costs during the production or service delivery processes. These activities whether direct production tasks or supporting functions, are seen as the true cost drivers, and it is these activities that should bear the costs in a way that accurately reflects how resources are consumed (Cooper and Kaplan, 1991). By focusing on these underlying activities, ABC provides a more accurate allocation of costs, enabling a deeper understanding of resource consumption and offering a better basis for decision-making, cost management, and process optimization.

Traditional cost accounting systems often rely on broad allocation methods, such as labor hours or machine time, which can fail to reflect the complexity of modern production environments. This can lead to inaccurate or misleading cost information (Jourdaine et al., 2022). ABC addresses this limitation by recognizing that products and services do not simply consume resources in a linear or proportional manner. Instead, they require a variety of activities that span different stages of production or service delivery. For example, manufacturing a product involves not only direct production activities, such as assembly, but also a range of supporting activities, such as procurement, quality control, setup, maintenance, and inventory management. ABC allocates costs to these activities and traces them to the products or services that require them, thus providing a more comprehensive and accurate picture of the true cost of production or service delivery.

The ABC methodology is based on several core concepts that work together to improve the accuracy of cost allocation (Skoda et al., 2009). One of the primary concepts is cost objects, which are the units for which costs are measured and assigned. These can include products, services, or even entire processes, and they represent the main focus of the ABC system. Cost objects serve as the endpoint to which all relevant costs are ultimately assigned, and their costs are calculated based on the activities required to produce them. For instance, if a company produces two types of products, each product would be a separate cost object, and the costs associated with the activities necessary for producing each product would be traced and allocated accordingly.

Another key concept in ABC is the cost driver, which refers to the factor or activity that causes or influences the cost to be incurred. Cost drivers are the activities that consume resources and drive the costs of producing goods or services (Babad et al., 1993). These drivers are central to the ABC methodology, as they reflect the true behavior of costs. For example, if quality control is a critical part of the production process, the cost driver could be the number of quality inspections performed. The costs associated with those inspections would then be allocated to the products or services that require them. By identifying cost drivers, ABC ensures that cost allocation is linked to the actual activities that cause the costs to arise, rather than relying on arbitrary or generalized allocation methods. This enhances the accuracy of cost information and provides a more realistic picture of cost behavior.

In contrast to traditional costing systems, which tend to focus on allocating costs based on volume-related metrics, such as labor hours or machine hours, ABC emphasizes the activities performed to produce goods or deliver services. This distinction is critical, as traditional methods may fail to account for the fact that costs are not always directly related to production volume. Instead, costs are often driven by the number or complexity of activities required to produce different products or services. For instance, a highly complex product may require more testing, higher-quality materials, and additional administrative support, even if production volume is low. ABC allows for the accurate tracing of these costs to the activities that generate them, whereas traditional methods might overlook such nuances.

The ultimate goal of ABC is to allocate production costs to products or services as accurately as possible by tracing those costs back to the activities that drive them. This level of detail provides organizations with a clearer understanding of where resources are consumed, which can highlight inefficiencies, redundant activities, or areas where costs are disproportionately high. Identifying such opportunities is valuable for companies seeking to improve operational efficiency, optimize resource utilization, and make more informed decisions about pricing, cost reduction, or process redesign. ABC provides businesses with valuable insights into which activities add value and which do not, thus enabling better decision-making related to resource allocation, pricing strategies, and process improvement.

To implement an ABC system effectively, several key steps are required. According to Miller (1992), these steps include: (i) cost classification, in which all costs within the organization are identified and categorized based on their relationship to activities. This step ensures that no costs are overlooked and that each cost is properly linked to an activity. (ii) Aggregation of actions into activities, which involves grouping similar tasks into broader activities that reflect cost generation. For example, tasks such as machine setup, inspection, and materials handling could be grouped under a broader activity such as "production support." (iii) Reporting the costs of activities, in which the costs associated with each activity are reported and allocated to the relevant cost objects. This step involves determining the cost drivers for each activity and using them to trace and allocate costs to the products or services that rely on those activities.

One of the main advantages of ABC is its ability to enhance cost visibility throughout the organization. By breaking down costs at the activity level, ABC enables businesses to pinpoint which activities consume the most resources and incur the highest costs. This level of insight can expose inefficiencies, bottlenecks, or areas where costs could be reduced through process improvement or automation.

Furthermore, ABC provides essential insights for strategic decision-making. Understanding the true cost of producing a product or service enables managers to make more informed decisions about pricing, outsourcing, or resource allocation. For example, businesses can adjust pricing based on the accurate cost structure of a product, ensuring that products are priced to reflect their true cost and thus improve profitability. Additionally, ABC can help identify underperforming products or services that may no longer be profitable, allowing companies to make data-driven decisions regarding product discontinuation or redesign.

In conclusion, activity-based costing (ABC) is a sophisticated and highly accurate method for allocating costs within an organization. By focusing on the specific activities that drive costs, ABC provides a detailed and realistic understanding of cost behavior, which is a significant improvement over traditional cost allocation methods. The use of cost drivers and the focus on activities enable organizations to identify inefficiencies, optimize resource usage, and make more informed strategic decisions. Although implementing ABC may require an initial investment of time and resources, the long-term benefits such as improved cost control, better decision-making, and enhanced process efficiency make it an invaluable tool for modern organizations seeking to improve their cost management strategies.

4.5 Blockchain Business Process Management Framework

The discipline that is concerned with the management of business processes is business process management (BPM). BPM encompasses the methodologies, tools, and technologies used to design, model, execute, monitor, and optimize business processes, aligning them with organizational goals and strategies (Zuhaira et al., 2021). The genesis of BPM can be traced back to the late 1990s, marking a pivotal convergence of information technology and management science (Viriyasitavat et al., 2022). Initially, BPM was largely confined to automating structured, repetitive tasks within organizations, yet, as technology advanced, so did the scope and sophistication of BPM. Modern BPM has evolved to encompass a holistic approach to process management, focusing on end-to-end process optimization, integration of diverse systems, and real-time monitoring and analysis (Khan et al., 2018). It is also defined as “the art and science of overseeing how work is performed in an organization to ensure consistent outcomes and to take advantage of improvement opportunities” such as cost, times and error rates reduction (Dumas et al., 1998 p. 1). Notably, business managers are attracted to BPM because of its demonstrated ability to deliver improvements in organizational performance, regulatory compliance and service quality (Dumas et al., 1998). This field of managerial studies is both actively practiced and actively researched (Dumas et al., 1998).

In a typical BPM initiative, performance measures to monitor and assess business processes are time, quality, cost, and flexibility: environmental impact is hardly considered a dimension to assess the performance of processes (T.M. Sohns et al. 2023). A business process can be defined as a "collection of inter-related events, activities and decision points that involve a number of actors and objects, and that collectively lead to an outcome that is of value to at least one customer" (Dumas et al., 1998, p. 5).

Systems that support the enactment and execution of processes have extensively been used by companies to streamline and automate intra-organizational processes. Yet, for inter-organizational processes, challenges of joint design and a lack of mutual trust have opened the discussion on new technological solutions.

Furthermore, Green business process management (Green BPM) is a new class of extended BPM practices for process design, execution, and monitoring, driven by the carbon footprint of business processes (Ghose et al., 2010). Green BPM is defined as "[…] the sum of all information system-supported management activities that help monitor and reduce the environmental impact of business processes in their design, improvement, implementation or operation stages […]". (Opit, Krup, and Kolbe, 2014, 3812). The focus of Green BM is the optimization of business processes with respect to sustainability aspects. to achieve this, Green BPM recognizes the salience of processes in resource consumption and carbon footprint generation and provides a process lens to guide companies in their implementation (Sohns, 2023).

Blockchain Business Process Management is a new topic in the BPM research agenda. To apply BPM it is important to define the *processes* relevant to the organization, i.e. the chains of events, activities and decisions that add value to the organization and its customers.

By investigating the definition of BPM a special interest is found in the characteristics of BPM that reflect the needs of enabling technologies of futuristic BPM (Viriyasitavat et al. 2023). The integration of blockchain technology with BPM presents a paradigm shift in how organizations manage and execute their operations, promising enhanced transparency, security, and efficiency across various business processes (Mendling et al., 2018). Managing business processes involves both processes and information flows; therefore, both information and process executions must be assured in BPM (Viriyasitavat et al. 2023). Modern BPM is characterized as dynamic, and decentralized process management, while preserving the basic functionalities of traditional BPM (Viriyasitavat et al. 2023). Specifically, Blockchain technology has garnered considerable interest within BPM because of its capacity to augment business process transparency, security, and efficacy (Taherdoost, 2024).

Several blockchains are adopted in various domains to facilitate the operation of new business processes such as the efficiency of Supply Chain Management through blockchain based smart inventory systems (Al Kurdi et al. 2022); the management of the food supply chain and the positive impact on consumer's perspective where blockchain plays a significant role in perceived security and privacy in developing trust, ease of use, and usefulness of blockchain-enabled systems (Kumar et al. 2022); the application to sustainable product management in the circular economy processes (Rusch et al. 2021); the application of blockchain in construction domain assuring better communication, understanding, documents sharing, stage transition and quality endorsement (Yang et al. 2020); and more.

According to an analysis of inter-organizational processes elaborated by Weber et al. (2016), inter-organizational business processes can be compiled from process models into smart contracts to ensure the joint process is correctly executed. The traditional BPM lifecycle (Dumas et al., 1998) has been redesigned (Mendling et al., 2018). Blockchains can help organizations to implement and execute business processes across organizational boundaries even if they cannot agree on a trusted third party (Mendling et al., 2018). Therefore, it can support the entreprise collaborations throughout the entire supply chain.

There are several requirements for the design of a blockchain process. In the context of architectural design, Alzhrani et al. introduced 12 architectural patterns for blockchain application software categorized into structural, interactional, transactional and security views.

Blockchain technology can facilitate business process execution and cross organizational collaboration in an automated manner, without the reliance on third parties (Mendling et al. 2018; Viriyasitavat et al. 2023). It is often defined as a replicated, append-only dataset, which has the major strength of maintaining tamper-proof distributed digital ledger of transactions that is updated based on consensus mechanism (Milutinovic et al., 2016; Lauster et al. 2020). The data recorded from business processes is available permanently and with the certainty, that no modifications have been made. The technical capabilities of Blockchains can help in solving the trust issue faced by companies engaging in shared business practices, since tamper-proof records of transactions are in place (Lauster et al. 2020). This integrity aware append-only technology helps in many businesses related use-cases and applications.

The core research of blockchain technology is based on efficient, secure, and scalable consensus algorithms. While public blockchain algorithms are scalable, permissioned blockchain algorithms are efficient and secure, but not sufficiently scalable. The most demanding property is to ensure data integrity i.e. to make sure not transactions are performed, updated or altered without the consensus mechanism within a network. This is generally ensured within an organization through implementation of cryptographic mechanisms (Ali, 2019).

Another demanded feature is establishment of trust which can be better obtained through consensus. Consensus governs addition of new items; it consists of the rules for validating and broadcasting transactions and blocks and resolving conflicts.

4.6 Blockchain-based Business Process Management Lifecycle

Furthermore, he considers the *trigger* components which allow the connection of these inter-organizational processes to Web services and internal process implementations. These *trigger* components serve as a bridge between the blockchain and enterprise applications. The cryptocurrency concept enables the optional implementation of conditional payment and built-in escrow management at defined points within the process, where this is desired and feasible (Mendling, 2018).

Blockchain-based smart contracts can eliminate many of the traditional obstacles that hinder the implementation of processes across multiple organizations. One key advantage is blockchain's function as a tamper-proof, transparent ledger, enabling stakeholders to trace a reliable record of interactions to identify where an issue may have occurred. As a result, every message that alters the system's state must be logged on the blockchain (Mendling, 2018). Furthermore, smart contracts can offer independent process monitoring from a global viewpoint, such that only expected messages are accepted, and only if they are sent from the player registered for the respective role in the process instance.

Finally, encryption can ensure that only the data must be visible in public, while the remaining data is only readable for the process participants that require it.

Even at this stage, research on the benefits and potentials of blockchain technology is mixed with studies that highlight or examine issues and challenges (Alam et al., 2021; Al-Farsi et al., 2021; Lu, 2019). Blockchain technology and its application to BPM are at an important crossroads: technical realization issues blend with promising application scenarios; early implementations mix with unanticipated challenges.

Blockchain can be closely related to the traditional BPM lifecycle (Dumas et al. 2018) providing some incremental changes.

The initial phase in the BPM Lifecycle is process identification, which involves a broad analysis of an organization from a process-centric viewpoint. This stage serves as a bridge between strategic goals and process enhancement efforts. Blockchain technology introduces a new dimension to this evaluation by highlighting potential strengths, risks, opportunities, and vulnerabilities. For instance, how can a business systematically pinpoint which processes are best suited for blockchain integration, or which are most at risk? Given blockchain's strong alignment with inter-organizational processes, this evaluation must extend beyond internal requirements to also consider known and unknown external stakeholders (Mendling, 2018).

Process discovery refers to the collection of information about the current way a process operates and its representation as an *as-is* model. Currently, methods for process discovery are largely based on interviews, and documentation analysis (Dumas, 2013). Blockchain technology defines new challenges for process discovery techniques. E.g., how can a company discover an overall process from blockchain transactions when these might not be logically related to a process identifier? Yet, an opportunity involves establishing trust in how a process or a prospective business partner operates, while a risk is that other parties might be able to understand operational characteristics from blockchain transactions.

Process analysis refers to obtaining insights into issues relating to the way a business process currently operates (Dumas, 2013). Currently, the analysis of processes mostly builds data that is available inside of organizations or from perceptions shared by internal and external process stakeholders (Dumas et al., 2018). Records of processes executed on the blockchain yield valuable information that can help to assess the case load, durations, frequencies of paths, parties involved, and correlations between unencrypted data items.

Process redesign deals with the systematic improvement of a process. Currently, approaches like redesign heuristics build on the assumption that there are recurring patterns of how a process can be improved (Clarkson, 2010). Blockchain technology offers novel ways of improving specific business processes or resolving specific problems. For instance, instead of involving a trustee to release a payment if an agreed condition is met, a buyer and a seller of a house might agree on a smart contract instead. The question is where blockchains can be applied for optimizing existing interactions and where new interaction patterns without a trusted central party can be established, potentially drawing on insights from related research on Web service interaction (Barros et al., 2005). A promising direction for developing blockchain appropriate abstractions and heuristics may come from data-aware workflows (Marin, 2012) and BPMN choreography diagrams (Decker and Weske 2011). Both techniques combine two primary ingredients of blockchain, namely data and process, in a holistic manner that is well-suited for top-down design of cross-organizational processes. Specific challenges for redesign include the joint engineering of blockchain processes between all parties involved, an ongoing problem for choreography design.

Process analysis refers to obtaining insights into issues relating to the way a business process currently operates. Currently, the analysis of processes mostly builds data that is available inside of organizations or from perceptions shared by internal and external process stakeholders (Dumas et al., 2018). Records of processes executed on the blockchain yield valuable information that can help to assess the case load, durations, frequencies of paths involved, and correlations between unencrypted data items. These pieces of information can be used to discover processes, detect deviations and conduct root cause analysis (Van Der Aalst, 2016).

Process redesign deals with the systematic improvement of a process. Currently, approaches like redesign heuristics build on the assumption that there are recurring patterns of how a process can be improved (Vanwersch, 2016). The question is where blockchains can be applied for optimizing existing interactions and their new interaction patterns without a trusted central party can be established, potentially drawing on insights from related research on Web service interaction (Barros, 2005). A promising direction for developing blockchain-appropriate abstractions and heuristics may come from data aware wok-flows and BPMN choreography diagrams (Decker, 2011). Specific challenges for redesign include the joint engineering of blockchain processes between all parties involved, and an ongoing problem for choreography design.

Process implementation refers to the procedure of transforming a to-be model into software components executing the business process. Currently business processes are often implemented using process-aware information systems or business process management systems inside single organizations. Some of the challenges regarding the transformation of a process model to blockchain artifacts are discussed by (Weber et al. 2016).

Execution refers to the instantiation of individual cases and their information-technological processing. Currently such execution is facilitated by process-aware information systems or business process management systems (Dumas, 2013). For actual execution of a process deployed on a blockchain following the method of Weber et al. 2016, several differences with the traditional ways exist. During the execution of an instance, messages between participants need to be passed as blockchain transactions to the smart contract; resulting messages need to be observed from the blocks of the blockchain.

Process monitoring refers to collecting events of process executions, displaying them in an understandable way, and triggering alerts and escalation in cases where undesired behavior is observed. Currently, such process execution data is recorded by systems that support process execution (Dumas et al. 2018). But data on the blockchain alone will likely not be enough to monitor the process but require an integration with local off-chain data. Based on monitoring data exchanged via the blockchain, it is possible to verify if a process instance meets the original process model and the contractual obligations of all involved process stakeholders. Blockchain technology can be exploited to store the process execution data and handoffs between process participants. Notably this is even possible without the usage of smart contracts, i.e., a first -generation blockchain like the one operated by Bitcoin (Prybila, 2017).

Adaptation and evaluation refer to the concept of changing the process during execution, in traditional approaches, this can for instance be achieved by allowing participants in a process to change the model during its execution (Reichert, 2012). Interacting partners might take a defensive stance to avoid certain types of adaptation.

Blockchain can be used to enforce conformance with the model, so that participants can rely on the joint model being followed. In such setting adaptation is by default something to be avoided: if a participant can change the model, this could be used to gain an unfair advantage over the other participants. The method proposed (Prybila, 2017) allows a runtime adaptation but assumes that relevant participants monitor the execution and react if a change is undesired.

There are also challenges and opportunities for BRM and blockchain technology beyond the classic BPM Lifecycle. Beyond the methodological support analysed above, there are the BPM capability areas including strategy, governance, information technology, people and culture (Rosemann and Vom Brocke, 2015).

Strategic alignment refers to the active management of connections between organizational priorities and business processes (Rosemann and Vom Brocke 2015), which aims at facilitating effective actions to improve business performance. Currently, various approaches to BPM assume that the corporate strategy is defined first and business processes are aligned with the respective strategic imperatives (Dumas et al. 2018). Yet, for many companies blockchain define a potential threat to their core business processes.

BPM governance refers to appropriate and transparent accountability in terms of roles, responsibilities, and decision processes for different BPM-related programs, projects, ad operations (Vom Brocke, 2010). Currently, BPM as a management approach builds on the explicit definition of BPM-related roles and responsibilities with a focus on the internal operations of a company.

Research on corporate governance investigates agency problems and mechanisms to provide effective incentives for intended behavior (Shleifer, 1997). Smart contracts can be used to establish new governance models as exemplified by the Decentralized Autonomous Organization (The DAO). The question is how far from the idea of the DAO can be extended towards reducing the agency problem of management discretion or eventually eliminate the need for management altogether.

As for Information technology blockchain enables novel ways of process execution, but several challenges in terms of security and privacy have to be considered. While the visibility of encrypted data on a blockchain is restricted, it is up to the participants in the process to ensure that these mechanisms are used according to their confidentiality requirements. Further challenges can be expected with the introduction of the General Data Protection Regulation, Guidelines for using private, public or consortium based blockchain are required (Mougayar 2016). It has also to be decided what types of smart contract and which cryptocurrency are allowed to be used in a corporate setting.

Also, the people who work as process analysts, process managers, owner or in other process-related roles are based on skills in the area of management, business analysis and requirement engineering. New skillsets are required related to partner contract management, software engineering, and cryptography. This implies that research into blockchain-specific technology acceptance is needed extending the established technology acceptance model (Venkatesh et al., 2003).

Finally, organizational culture defined as the collective values of a group of people in an organization (Rosemann and vom Brocke 2015). Blockchains are likely to influence organizational culture towards a stronger emphasis on flexibility and an outward-looking perspective. In the competing values framework by (Cameron and Quinn 2005), these aspects are associated with an adhocracy organizational culture. Furthermore, not only consequences of blockchain adoption have to be studied, but also antecedents.

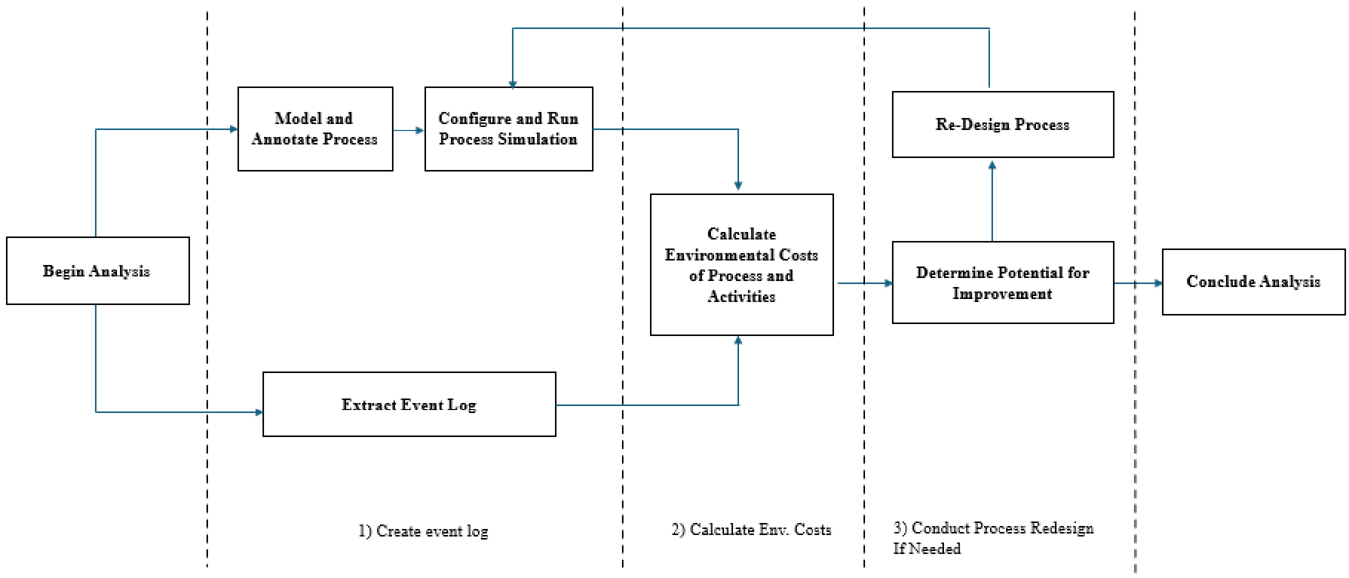
Nonetheless, sustainability solutions may not lie in increasing the efficiency of technologies and the effectiveness of economic incentives but instead may need to be facilitated by organizational setups and sociocultural frameworks defining the purpose of technologies and economic instruments (Göpel 2016.

4.7 Data Sources and Analysis Procedure

Primary data was obtained from the field research at a waste management facility in Guidonia (RM). The primary data concerns the as-is process of waste management collected through observation and in person confrontation with the facility's management. Secondary data were collected from a desk review collecting data from various sources which included reports, literatures regarding waste management and reputable periodicals, magazines and public databases with statistical data were considered.

Data analysis method follows the procedures listed under the following sections. SOPA outlines a three-step method for evaluating the environmental impact of business processes and guiding their sustainability-oriented redesign. When applying SOPA, two main scenarios are possible. In the first, existing event logs containing data from actual process executions are examined to identify opportunities for improvement, this is known as log-based analysis. In the second, a process model is assessed using Business Process Simulation (BPS), referred to as model-based analysis. These approaches form the basis of SOPA's three core steps: One option involves creating and annotating a process model, which is then simulated to produce synthetic execution data for analysis. Alternatively, real execution data can be obtained by extracting an event log from the relevant information system.

Table 8 - SOPA Application procedure



Source: Klessacheck et al. 2024

To begin a model-based analysis, the process must first be represented as a model, typically using a process modelling language such as BPMN (OMG, 2011). Activities serve as the fundamental building blocks of both processes and their corresponding models. Next, this execution data is combined with Life Cycle Assessment (LCA) data to determine the environmental impact of the overall process and its individual activities. If the analysis reveals a need for process redesign, simulation can be applied further to explore and evaluate potential improvements.

The third and final phase of SOPA, illustrated, focuses on sustainability-driven process redesign. If the analysis of calculated environmental costs reveals areas for improvement, such as unusually high average environmental costs for certain process instances or activities, or lower-than-anticipated reductions, then the process can be modified accordingly.

After setting up a new simulation run, the resulting event log can be re-evaluated, allowing for a comparison of cost analyses. Based on the outcomes, it may be necessary to initiate another redesign cycle or proceed with implementing the proposed redesign in practice. Additionally, the process analyst might assess whether achieving the potential environmental impact reduction is financially viable and adjust the redesign scenario to better balance environmental and economic factors.

To increase the exactness of simulation, the information can be based on the analysis of event logs (Pufahl 2018; Wynn et al. 2008). Furthermore, the use of LCA scores to compare the environmental impact of activities and processes could cause discrepancies in data because of incomplete or inconsistently elicited data (SOPA). To deal with this risk in the model the quality of data and model has been curated by finding a consensus on data with stakeholders. Furthermore, conflicts among the environmental, social and economic perspective of sustainability may arise since one of these three facets might have a negative impact on the other. (e.g. a reduction in environmental impact might have a substantial impact on cost increase). To strengthen the SOPA approach and combine the environmental dimension of sustainability with the economic and social dimension, the Life Cycle Sustainability Assessment (LCSA) has been adopted.

4.8 Validity and Reliability

Reliability has numerous definitions and approaches. In this study reliability was enhanced by procedures in a case study protocol. Furthermore, internal validity was strengthened by data triangulation (i.e. organizational documents, essays, in-depth interview). The notion of plausibility is about how field research is made sensible and believable (Baxter and Chua, 2008). In this research it is addressed by several elements. First, the lack of analysis protocols and reference is overcome by the choice of implementing and existing research framework. Second, having set up the project, the data analysis process was driven by research questions that explores the impact of blockchain technology on rural areas. Rigorous and systematic analysis was performed in terms of coding and reviewing the data available (Hutchison et al., 2010).

When data is collected through qualitative research methods, the question of integrity, quality and reliability is extremely important, as reliability is synonymous with consistency. (Easterby-Smith, 2009), Merriam (2009) and Creswell (2013) propose that it is necessary to specify terms and ways of establishing ad assessing the trustworthiness and reliability of qualitative research that provide an alternative to reliability and validity in quantitative research approaches. The two primary criteria for assessing a qualitative study are trustworthiness and authenticity. In strategic management research, like in other social sciences research, trustworthiness in qualitative studies comprises four criteria or tests: (i) credibility (internal validity); transferability (external validity); data dependability (reliability; and confirmability (objectivity). These four criteria were incorporated in the study to establish integrity and rigour in the qualitative case study.

By implementing the case study protocol to guide the study, the integrity, credibility and reliability of the study was increased.

As for validity, in this study the researcher was guided by reviewed literature related to green business process management. Additionally, the literature analysis conducted prior to the main study and SOPA method application assisted the researcher to avoid uncertainties of the contents in the data collection measuring instruments. The choice of SOPA method is based on several motivations. First while other approaches focus on individual enterprises or processes, and are not intended to cross organizational boundaries, SOPA is useful to capture the entire environmental impact of processes or organizations. SOPA offers a tool for optimizing the environmental impact of business processes. An unanswered question remains: are BPM techniques applicable for improving the sustainability of business processes?

Table 9 - Case Study methodology description

Outline of the case study	The outline of the case study incorporated a literature review, case study objectives and issues
Field Procedures	Access to waste management processes
Case study questions	Questions the investigator developed for collecting data and the sources of data and information needed to answer each question. In this study a semi-structured interview schedule guided data collection.
A guide for the study report	Outline, format of the narrative, and specifications of any bibliographical information and other documentation provided.

Source: Adaptation from Gaya & Smith, 2016

Chapter 5. Blockchain Waste Management Case Study

Based on the premises of the methodological chapter, this chapter presents a single case study exploring the implementation of blockchain technology in waste management within the waste management facility in a protected natural area in the roman provence. The case study describes and examines data collected from the primary source of the waste management facility (5.1). The process is then designed in the *as-is* version to analyze and identify the main transactions and data bases used for storing information on the waste processed. Based on this primary analysis the initial evaluation is made following the SOPA methodological process (5.2).

Subsequently, through the data collected, the *to-be* blockchain waste management model is designed following BPMN rules and evaluated using the SOPA evaluation methodology (5.3).

Finally, a comparative analysis is made to estimate the environmental impact of blockchain technology on waste management (5.4). By analyzing this practical blockchain waste management implementation, this chapter aims to uncover insights that inform both theory and practice, contributing to the broader discourse on innovation and sustainable waste management.

5.1 Data Collection

The data collection for this research is based on primary and secondary data sources. The primary data collection source is the waste management facility through the declarations of the facility management in occasion of a field visit in the waste management center. This data is hereafter used to initially model the *as-is* process. The secondary data is retrieved from the LCA database and public databases where information has been extracted and collected to evaluate the *as-is* process. In this paragraph the data collection process is described (5.1.1) by describing the case study and providing a background of the waste management case selection. Subsequently, (5.1.2) the *as-is* process description is presented applying the Camunda software. Finally, the environmental and economic cost of the process is evaluated.

5.1.1 Case study description

The area of the Inviolata Park located on the eastern outskirts of Rome is notable for its high environmental diversity with a mix of waterways with wetland vegetation, gallery forests, oak woodlands, cultivated fields, pastures, hedgerows, tuff gorges with cliffside flora (Ente Regionale RomaNatura). This variety of habitats supports a rich botanical and faunal biodiversity, making the park an important site for nature conservation. There are several animal species found in the area, many of which are now rare in the Roman countryside and the Lazio region. Ongoing research has identified numerous insect and vertebrate species, several of significant conservation interest (Cervoni et al. 2018).

Waste management challenges in the Inviolata Park area mirror those commonly found in rural regions. Despite its proximity to Rome, the park's diverse and sensitive environment including wetlands, woodlands, cultivated fields, and unique geological features faces pressures similar to those in rural settings, where dispersed populations and fragmented infrastructure complicate effective waste collection and disposal. The rich biodiversity, including many rare and protected species, further elevates the importance of sustainable waste practices to prevent pollution and habitat degradation. Consequently, managing waste in this area requires approaches that address both environmental protection and logistical constraints typical of rural waste management contexts.

Beyond its ecological importance, the park is also the site of major historical and archaeological discoveries. Among the most significant is the 1992 discovery of the only complete Capitoline Triad, a marble sculpture group representing Jupiter, Juno, and Minerva seated on a single throne. Another important find is the painting of the Blessing Christ, discovered (and later stolen) in the rupestrian church of Marco Simone within the park. After its recovery, the artwork was placed in the "Lanciani" Museum of Guidonia Montecelio, where the Capitoline Triad is also housed (Ente Regionale RomaNatura, n.d.).

Originally entrusted to the municipality of Guidonia Montecelio, the area was exposed for twenty years to intense building speculation, as the town rapidly grew to become the third largest in Lazio, now home to 80,000 residents. However, with the recent approval of Regional Law No. 12 on August 10, 2016 (published in the Official Bulletin of the Lazio Region on August 11, 2016, No. 64 - Special Issue No. 2), management of the protected area was transferred to the Monti Lucretili Regional Natural Park.

5.2 *As-Is* Process Description

In the following paragraph the *as-is* process is described presenting the primary source data collected during a field visit in the waste management facility in Guidonia.

The waste facility selected for this study is responsible for handling the dry fraction of municipal solid waste, although the waste stream often contains organic components which are separated and treated separately in the same waste management site.

The waste treatment process begins upon unloading by incoming transport vehicles which are mainly transporting waste from the municipality of Rome. Upon arrival at the company's facility, the vehicles are weighed and documented. Documentation is carried out via standardized forms known as the FIR (Formulario di Identificazione dei Rifiuti) using a digital centralized platform. The data include the weight of the waste load, vehicle information, driver identification, the originating company, and the type of waste along with its corresponding European Waste Catalogue (EWC) code[23]. The documentation complies with the updated RENTRI (Registro Elettronico Nazionale per la Tracciabilità dei Rifiuti) regulations[24].

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[23] The European Waste Catalogue (EWC) is a structured classification system for waste types, created under Commission Decision 2000/532/EC2. It consists of twenty main categories, most of which relate to specific industries, while others are organized by material types or processes.

[24] The EWC system forms a foundational element for waste reporting and classification, operating in parallel with regulatory frameworks such as RENTRI, which is discussed in detail in Chapter 3.

Following registration, the waste is subjected to a radiometric screening[25]. This step is essential to detect potential radioactive contamination, which may occur in materials such as hospital-derived waste (e.g., incontinence pads from oncology patients) or natural materials (e.g. tuff which however is usually processed further because not considered hazardous).

The waste is then unloaded into a closed area equipped with a forced-air ventilation system[26]. Here, the contents are removed from their bags and conveyed to a biofilter (a basin filled with organic material, e.g. a mixture of wood and peat) designed to degrade airborne pollutants, including odorous compounds, in compliance with environmental emission standards. The facility is fitted with automated doors to contain emissions during operations.

Mechanical sorting is employed to separate the waste based on particle size: smaller fractions typically include residual organic material. The stabilization process that follows, which lasts approximately 25 days, makes the material chemically inert[27]. During stabilization, aerobic conditions are maintained to promote microbial degradation of organic matter, raising the temperature to 65-70 °C. This aerobic process prevents the formation of methane[28] by continuously supplying oxygen.

The resulting stabilized output is a less polluting, lighter compost-like material, which is sent either to landfills located outside the region or to waste-to-energy (WTE) plants. The remaining fraction, consisting mainly of paper and plastic, is deemed non-recyclable due to contamination. This material

[25] Radiometric monitoring is the inspection of scrap, semi-finished, and all other metal materials to detect radioactive anomalies.

[26] The forced air ventilation system provides ventilation for the contaminated or potentially contaminated areas.

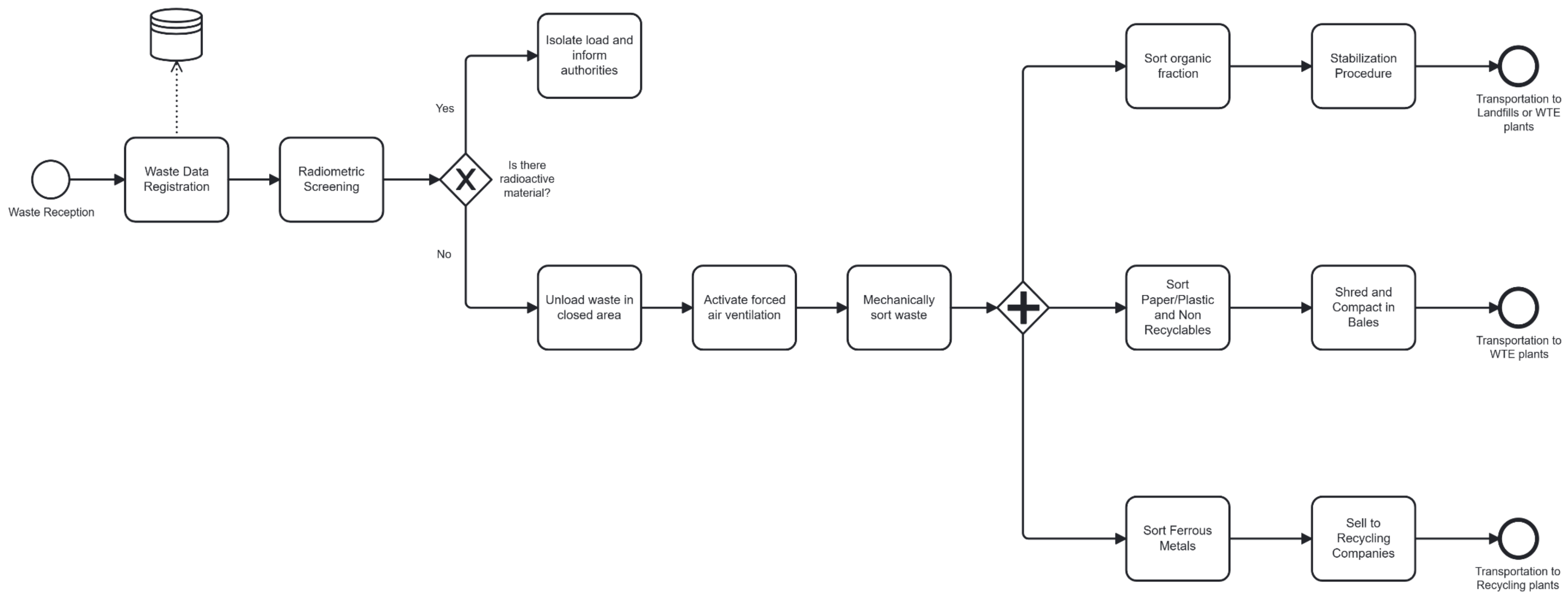
[27] This refers to a process by which a substance is transformed into a chemically stable and non-reactive state. This is particularly relevant in waste treatment, where potentially hazardous materials are treated to eliminate their chemical reactivity, thereby minimizing environmental and health risks.

[28] The waste sector contributes nearly 20% of anthropogenic methane emissions. Targeted interventions in solid waste and wastewater management could cut emissions by up to 36 million tonnes annually by 2030, while offering health, environmental, and economic co-benefits. Many of these measures are low-cost or cost-saving. Addressing methane from waste is essential for improving global waste management and should align with the waste hierarchy: prevention, re-use, recycling, energy recovery, and landfill disposal as a last resort (UNEP and CCAC, 2021).

is shredded, compacted into bales, and sent to WTE facilities. Ferrous metals are extracted via magnetic separation and constitute a secondary resource market, being resold to companies for recycling. The entire operation is managed by staff from 6:00 a.m. to 2:30 p.m., five days a week. This shift-based organizational structure is designed to distribute operational responsibilities effectively.

The process description has been modelled (Fig. 2) applying BPMN language and represented with the use of Camunda, a process design, orchestration and automation platform used in enterprises (Geiger et al., 2018; Nikolova et al., 2024). Camunda is a Java-based platform designed for workflow and process automation, built around BPMN models. It provides a comprehensive suite of tools for modelling, executing, and automating business processes.

FIGURE 2 - WASTE MANAGEMENT PROCESS BASED ON CASE STUDY DESCRIPTION.



Source: Authors's own elaboration

The waste management process is subject to several intermediate outputs which can be part of circular economies. To thoroughly analyze the process, the final outputs are outlined in Table 8.

Table 10 - Waste Management Outputs, treatments and final destinations.

Output	**Treatment**	**Destination**
Compost	Stabilization	Landfills or WTE plants
Paper	Shredding and compacting into bales	WTE plants
Plastic	Shredding and compacting into bales	WTE plants
Ferrous metals	Extraction through magnetic separation	Secondary resources market

Source: Author's elaboration.

The table outlines a systematic approach to the post-sorting treatment and final destinations of various waste streams within an integrated waste management framework. Organic waste, once subjected to stabilization typically via aerobic composting or anaerobic digestion is rendered into compost. However, due to quality or contamination concerns, this compost is not always suitable for agricultural application and is often redirected to landfills or WTE facilities. Inorganic recyclables such as paper and plastic undergo mechanical processing involving shredding and compaction into dense bales. These are not recycled in this context but instead serve as high-calorific input for WTE plants, highlighting a trade-off between material recovery and energy recovery. Ferrous metals are extracted from the waste stream through magnetic separation, a common and efficient technique in material recovery facilities. Unlike the organic and high-energy fractions, these metals are directed to the secondary resources market, where they are reintroduced into industrial supply chains. This system underscores a hierarchy of waste valorisation strategies prioritizing energy recovery where material recycling is less viable, and ensuring circularity where purity and market viability permit.

Following the process description and modelling, it is essential to articulate a set of final considerations that illuminate the critical pain points observed in the waste management process at the selected facility. First, the plant operates in alignment with the RENTRI model, a centralized waste tracking system introduced under recent Italian waste management legislation. However, this model presents significant limitations, particularly its lack of integration with end-destination data flows. The facility does not receive or exchange information regarding the final treatment or disposal of waste once it leaves the site (e.g., when transported to landfills or incineration plants in other regions or countries). This absence of feedback impedes full process transparency and lifecycle accountability. Second, the facility relies on manual data entry into its information system, a practice that introduces inefficiencies and undermines data reliability. The current approach is heavily dependent on self-declared records, which are difficult to verify and may affect the integrity of operational and compliance reporting. Furthermore, the facility is situated within the Inviolata Regional Park, a protected natural area, and has been the subject of recurring public criticism, particularly from residents and the Guidonia Municipality. Concerns have been raised regarding its potential contribution to environmental pollution and its impact on public health. Despite the facility's official claims of adhering to pollution mitigation standards and promoting sustainability in its operations, the lack of transparency and stakeholder trust presents a reputational risk and raises broader questions about the effectiveness of environmental governance and monitoring mechanisms in the region.

5.3 *As-Is* Process Evaluation: As-Is Process Analysis

Based on the initial consideration on the process of waste management described and mapped, the aim is to understand the impact of the waste management process as it is (*as-is*). In order to evaluate the process, the mapping into single activities has been carried out. This is an essential step since activities are the main components of a process and therefore its identification is functional to the evaluation of its environmental and economic cost. In this research the following definition of "activity" is applied (Klessascheck et al., 2025):

“**Definition 1** (Activity) Let A be the universe of all possible activities. Then *a* ϵ *A* is a single activity that can be enacted during process execution.”

To systematically assess the environmental and operational performance of the waste management process under study, the workflow was disaggregated into five primary activity codes (A1 - A5), each representing a distinct phase within the treatment and disposal chain. Activity A1, *Waste Data Registration*, includes the reception and weighing of incoming transport vehicles, along with the manual input of documentation into the RENTRI (Registro Elettronico Nazionale per la Tracciabilità dei Rifiuti) database, which reflects current regulatory compliance procedures. Activity A2, *Radiometric Screening*, functions as a control gate to detect any radioactive contamination, ensuring safe handling and environmental protection. Activity A3, *Waste Sorting*, comprises the mechanical separation of materials, such as organic, ferrous, paper, and plastic fractions and is supported by auxiliary operations including waste unloading and the operation of biofiltration systems to manage odor emissions. Activity A4 involves *Stabilization, Shredding, and Compacting*, which includes a 25-day aerobic stabilization process to reduce the biological reactivity of waste and the subsequent compaction of non-recyclable residues. Finally, Activity A5 covers the *sale and transfer of recyclable fractions* to external recycling companies or waste treatment plants. This structured breakdown of activities serves as the analytical basis for mapping material flows, evaluating energy and emissions data, and modeling the potential environmental trade-offs introduced by technological interventions such as blockchain integration.

Table 11 - List of Activities in the *As-Is* Waste Management Process

Code	**Activity Description**	**Sub-Activities**
A1	Waste Data Registration	Receive and weigh transport vehicle
A1	Waste Data Registration	Manually Register documentation (RENTRI database)
A2	Radiometric screening	-
A3	Waste Sorting	Unload waste into ventilated area
A3	Waste Sorting	Operate biofilter

A3	Waste Sorting	Mechanical sorting of organic, ferrous, paper and plastic materials
A4	Stabilization/ Shredding Procedures/Compacting	Stabilization (25-day aerobic process)
A4	Stabilization/ Shredding Procedures/Compacting	Compact and bale non-recyclable material
A5	Selling to Recycling Companies and Waste Recycling Plants	-

Source: Author's own elaboration.

Subsequently, based on each activity, the abstract environmental cost drivers are annotated. The abstract environmental cost drivers describe the objects, resources and products involved in the execution of the specific activities.

Table 12 - Abstract environmental Cost Driver in the *As-Is* Process Model.

Code	**Abstract Cost Driver**	**Description**
AD1	Vehicle fuel consumption	Emissions from transport trucks
AD2	Paper usage	For FIR forms, administrative records
AD3	Server/IT infrastructure	For RENTRI and tracking systems
AD4	Screening Operation	Operation of Radiometric screening machines
AD5	Ventilation system operation	Forced-air system to prevent emissions
AD6	Biofilter organic material	Wood/peat mixture replaced periodically
AD7	Sorting machine operation	Mechanical separation of materials
AD8	Stabilization aeration system	Blowers, rotors to keep aerobic conditions
AD9	Bale wrapping plastic	Plastic used for compacting bales
AD10	Landfill methane potential	Estimated potential for landfill gas generation
AD11	Vehicle fuel consumption	Emissions from transport trucks

Source: Author's elaboration.

Based on the abstract environmental cost drivers, the concrete environmental cost drivers are identified (e.g. the type of fuel used for transportation purposes may influence the environmental costs). These concrete drivers represent specific, measurable inputs or emissions factors that can be directly linked to Life Cycle Assessment (LCA) datasets. The table presented captures a variety of alternatives for each operational component of the process, enabling scenario-based simulation and comparative analysis of environmental performance. For instance, vehicle fuel consumption (D1) is modelled using distinct transport technologies, including diesel-powered Euro 6 trucks, compressed natural gas (CNG) vehicles, and electric trucks drawing power from the regional grid mix. Electricity usage (D2) is differentiated by source, allowing comparisons between conventional grid electricity and photovoltaic (PV)-generated electricity. Document-related impacts (D3) are captured by specifying standard A4 copy paper versus recycled paper alternatives, while IT infrastructure (D4) contrasts cloud-based storage with on-premise servers, measured by energy use per unit of data per month.

Ventilation (D5) and stabilization (D8) systems are modelled in terms of energy consumption per unit of airflow or per ton of processed material, respectively. Biofilter inputs (D6) are linked to specific LCA records such as EU-sourced peat (PEAT-001) and shredded wood biomass (WOOD-004), enabling traceability and normalization within standardized environmental databases. Bale wrapping materials (D9) include low-density polyethylene (LDPE) film and emerging alternatives such as compostable bio-based wraps. Emissions from downstream processing (D10, D11) are quantified using regionalized WTE (waste-to-energy) emission factors and methane generation potentials from organic waste in landfills. Finally, logistical and operational impacts are represented through specific transport modes and distances (D13), energy consumption by magnetic separators (D12), and building-related emissions from heating systems and employee commuting (D14), based on activity data and regional emission factors.

Table 13 - Concrete Environmental Cost Drivers in the *As-Is* Process.

Code	Concrete Environmental Cost Drivers
D1	Diesel (Euro 6 truck), CNG truck, Electric truck (with grid mix)
D2	A4 copy paper (80g/m²), recycled paper
D3	Italian grid electricity mix, PV-sourced electricity
D4	Italian grid electricity mix, PV-sourced electricity
D5	Aeration system blower (kWh/day per ton)
D6	Peat from EU (LCA ID: PEAT-001), shredded wood (LCA ID: WOOD-004)
D7	Magnetic separator energy (kWh per ton)
D8	Industrial air handler (kWh/unit of flow)
D9	LDPE film (per kg), compostable wrap
D10	Methane (CH_4) emission factor per ton of organic material
D11	Truck transport 100km (Euro 6), rail transport 200km
D12	Diesel (Euro 6 truck), CNG truck, Electric truck (with grid mix)
D13	A4 copy paper (80g/m²), recycled paper
D14	Italian grid electricity mix, PV-sourced electricity

Source: Authors' elaboration.

With the aim of explaining the relation between abstract and concrete environmental cost drivers the definition is presented as follows (Flessacheck et al., 2025):

"**Definition 2** (Environmental Cost Driver Hierarchy) let D be a set of abstract environmental cost drivers, where $d \in D$ is a single environmental cost driver. Let C be a set of concrete environmental cost drivers, where c $\in$ C is a single concrete environmental cost driver. Finally, let H be a hierarchy of abstract and concrete environmental cost drivers, so that $H \subseteq D \times C$. This means that abstract environmental cost drivers $d \in D$ has one or more concrete environmental cost drivers $c \in C$ associated with it."

Subsequently, for each concrete environmental cost driver, a concrete, LCA-defined impact score is determined through manual LCA analysis. This is realized through a cost function described in

Definition 3 (Flessacheck et al., 2025), where for each concrete environmental cost driver, the impact score is returned.

“**Definition 3** (Cost Function) Let C be a set of concrete environmental cost drivers. Cost functions assign concrete environmental costs in terms of impact on sustainability to concrete environmental cost drivers. More specifically, let cost be a cost function of concrete environmental cost drivers so that $cost : C \rightarrow \mathbb{Q}$ assigns environmental cost values to concrete environmental cost drivers.”

5.4 *As-Is* Process Evaluation: Environmental Cost Calculation

Defining the activities on which the abstract environmental costs and the concrete environmental costs are based, is functional for the environmental cost calculation. The objective is to gain insights into the environmental impact of a process by considering its process and activity instances.

As outlined earlier, conducting a model-based analysis necessitates the specification of precise Life Cycle Assessment (LCA) values for the environmental cost drivers linked to activity instances during the simulation setup phase. In the case of log-based analysis, the event log must contain adequate detail either by directly providing LCA values for specific activities or by including information about abstract environmental cost factors along with rules for their concretization.

When an event log is available that records process executions and includes LCA scores representing the environmental impacts of the associated cost drivers, an Activity-Based Costing (ABC) approach can be employed to estimate the total environmental burden of the process. This allows for the calculation of the environmental cost for each individual activity or process instance. The following section formally introduces the core concepts and presents the methodology used to compute environmental impact scores.

The concrete environmental cost drivers for each concretization of the environmental cost drivers is provided in Table (16).

Table 14 - Concretization of the environmental cost drivers (*As-Is*).

Code	Concrete Cost Driver	Functional Unit	Emission Factor (kg CO_2e)	Emission Factor (kg CO_2e)
CD1	Diesel (Euro 6 truck), CNG truck, Electric truck (with grid mix)	per tkm	0,084	$8{,}4 \times 10^{-2}$
CD2	A4 copy paper (80g/m²), recycled paper	per sheet (5g)	0,006	$6{,}0 \times 10^{-3}$
CD3	Italian grid electricity mix, PV-sourced electricity	per kWh	0,18	$1{,}8 \times 10^{-1}$
CD4	Italian grid electricity mix, PV-sourced electricity	per kWh	0,18	$1{,}8 \times 10^{-1}$
CD5	Aeration system blower (kWh/day per ton)	per day-ton (12 kWh/day)	2,16	$2{,}16 \times 10^{0}$
CD6	Peat from EU (LCA ID: PEAT-001), shredded wood (LCA ID: WOOD-004)	per kg	0,65	$6{,}5 \times 10^{-1}$
CD8	Magnetic separator energy (kWh per ton)	per ton processed (8 kWh)	1,44	$1{,}44 \times 10^{0}$
CD7	Industrial air handler (kWh/unit of flow)	per kWh	0,18	$1{,}8 \times 10^{-1}$
CD8	LDPE film (per kg), compostable wrap	per kg	2	$2{,}0 \times 10^{0}$
CD9	Methane (CH_4) emission factor per ton of organic material	per ton	850	$8{,}5 \times 10^{2}$
CD10	Truck transport 100km (Euro 6), rail transport 200km	per 100 km (10t load)	84	$8{,}4 \times 10^{1}$

In assessing the environmental impacts of concrete production and associated supply chain activities, it is critical to quantify the greenhouse gas emissions associated with various material and energy inputs, as well as transport modalities. Table 16 summarizes key environmental cost drivers, their functional units, and corresponding emission factors expressed in kilograms of CO_2 equivalent (kg CO_2e). For transportation, diesel trucks compliant with Euro 6 standards emit approximately 8.4×10^{-2} kg CO_2e per tonne-kilometer (tkm), while compressed natural gas (CNG) trucks and electric trucks powered by the EU electricity grid exhibit lower emission factors of 6.8×10^{-2} and 4.5×10^{-2} kg CO_2e per tkm, respectively (ecoinvent v3.9; DEFRA; grid emissions based on ISPRA/Terna 2023). The electricity grid's emission intensity is estimated at 1.8×10^{-1} kg CO_2e per kWh, contrasted with photovoltaic-sourced electricity at 4.5×10^{-2} kg CO_2e per kWh (IPCC/IEA). Material inputs such as LDPE film contribute significantly to emissions (2.0×10^{0} kg CO_2e per kg), while compostable wraps demonstrate lower emissions (8.0×10^{-1} kg CO_2e per kg). Waste treatment processes also represent substantial emissions: incineration of dry waste reaches up to 4.0×10^{2} kg CO_2e per ton, and landfilled organics associated with methane release emit 8.5×10^{2} kg CO_2e per ton (ecoinvent; IPCC). Energy use for industrial equipment such as sorting lines and aeration blowers further adds emissions at 1.44 and 2.16 kg CO_2e per ton processed or per day-ton, respectively. These emission factors provide a foundational basis for life cycle assessment modelling and enable targeted mitigation strategies across the concrete supply chain.

Definition 4 (Activity Instance) Let the set of activity instances I be a set $I \subset A \times P(C)$, where each activity is associated with a set of concrete environmental cost drivers. A single activity instance $i \in I$ therefore am a pair (a, Q), with $a \in A$, $Q \in P(C)$.

Definition 5 (Process Instance) A process instance is a finite non-empty sequence of activity instances, containing totally ordered pairs of activity instances and sets of concrete environmental cost drivers. Let $I \subset A \times P(C)$ be an alphabet of activity instances. Then, $I*$ is the set of all finite sequences of activity instances, which are also called process instances. Thus, let $t \in I*$ be a single process instance, which contains one or more pairs (a, Q).

5.5 Process Re-Design

The third and final stage of the SOPA framework addresses the re-design of business processes with a focus on sustainability. This phase is initiated when the analysis of computed environmental costs indicates areas with potential for ecological optimization for instance, when process instances exhibit unexpectedly high average environmental impacts, specific activities contribute disproportionately to the overall footprint, or anticipated reductions are not achieved. In response to such findings, the process may be restructured or adapted to improve its environmental efficiency.

Building on the waste management process model introduced in the previous section, a new system architecture is proposed. The process architecture utilizes a blockchain-based platform designed to function as a traceability and monitoring solution, effectively replacing the functionalities of the RENTRI system. It is integrated with a distributed database infrastructure, also based on blockchain technology, which enables the inclusion of waste treatment and disposal facilities located outside the originating region or even across national borders, where waste and its final outputs may be transported. The blockchain platform is responsible for defining and recording all entities and stakeholders involved in the waste management lifecycle. It maintains records of key assets, including waste handling facilities, landfills, and repositories, and supports the classification of local waste types as well as the mapping (or translation) between differing classification schemes. Additionally, the system captures and stores a complete, immutable log of all process executions, including detailed information such as timestamps, waste categories, quantities, involved assets, and responsible parties. To facilitate analysis of the blockchain-based waste management process, access to the technical data embedded within waste transaction records is essential.

The integration of blockchain technology into waste management systems is hypotetized by leveraging the immutable and decentralized nature in each stage of the process, from initial registration to final sale or reuse. First, at the registration stage, blockchain facilitates the verification of waste origin, thereby improving traceability and ensuring adherence to compliance standards. During screening and inspection, the secure logging of radiation tests contributes to safety assurance by creating a tamper-proof record. Incident reporting is similarly strengthened through automated, verifiable notifications to regulatory authorities, enhancing both transparency and legal accountability. In the stages involving waste transfer and sorting, blockchain supports the maintenance of chain-of-custody integrity, reducing the risk of data manipulation or unauthorized handling. The management of recyclables and organic waste further benefits from real-time tracking of material flows and environmental data, enabling fraud prevention and supporting third-party auditing and certification processes. Finally, the documentation of transactions related to the final use or sale of waste materials enhances supply chain transparency. In figure (X) the waste management process model is therefore presented in the *to-be* version where blockchain technology is implemented as stated.

Table 15 - Technical information of a waste transaction

Field	**Description**
Transaction Type	One of the transaction types defined in Table I
Transaction identifier	Identifies the transaction
Source	Identifies the source transaction
External references	References to an external (usually local) system
Signature	Signature based on the data above

Source: Author's own elaboration.

5.6 To-Be Process Modeling and Evaluation

The blockchain consensus protocol is the most debated issue when analysing the impact of this technology on energy consumption and therefore on sustainability. The emergent protocols are seeking solutions to address the blockchain trilemma which addresses a set of three main issues: decentralization, security, and scalability. But as emergent protocols seek solutions to address the trilemma, attention is due to the fourth pilar which is found in sustainability, or how the protocol impacts on the environment.

Blockchain-based distributed ledger technologies (DLTs) rely on a variety of computational and infrastructural components, resulting in energy consumption through multiple pathways (Ahl et al., 2019). The primary source of energy use in such systems is the electricity required to power the computational hardware that executes blockchain client software and consensus algorithms. However, additional indirect energy expenditures must be considered, including the energy consumed in the manufacture and lifecycle of mining or validating equipment, and the operational energy overhead associated with data transmission across the network infrastructure (Seldmeyr et al., 2020; Rukhiran et al., 2024).

The environmental impacts arising from blockchain-related energy consumption are multifaceted. Of principal concern is the generation of greenhouse gas (GHG) emissions associated with electricity production. While energy use and emissions are not strictly linearly correlated, owing to regional differences in grid carbon intensity empirical studies demonstrate a strong underlying relationship between the two. Secondary environmental burdens, such as deterioration of air quality, freshwater resource depletion, and land-use impacts, also result from energy production and infrastructure deployment. However, these dimensions fall outside the scope of the present analysis (Rukhiran et al. 2024).

Electricity consumption by blockchain networks leads to GHG emissions that contribute significantly to anthropogenic climate forcing (Taskinsoy, 2019). The magnitude of these emissions is contingent on two key variables: the total electricity consumed by the network and the emissions intensity of the electricity mix used. In permissionless public blockchains, where transaction data are broadcast to and recorded by globally distributed nodes, this electricity consumption can be considerable. Given that the recording of a transaction on a blockchain represents the fundamental unit of data persistence, measuring energy consumption on a per-transaction basis offers a practical proxy for evaluating the environmental efficiency of blockchain systems.

The process by which transactions are added to a distributed ledger typically begins with a user broadcasting a transaction to the network. These transactions are collected by validator or block-proposing nodes and held temporarily in a memory pool ("mempool") pending inclusion. Block proposers then bundle transactions into candidate blocks, applying a suite of validity checks—including, but not limited to, cryptographic verification of digital signatures and account balance sufficiency. The finalized block is then subjected to the network's consensus protocol, which may be based on proof-of-work (PoW), proof-of-stake (PoS), Federated Byzantine Agreement (FBA), or another consensus mechanism (Nguyen et al., 2019; Xiao et al., 2020).

It is important to note that transaction inclusion is neither guaranteed nor compulsory; many blockchain systems allow for blocks to be published that contain no transactions. However, economic incentives are typically in place to encourage inclusion. Transaction fees, often set by the sender, serve to prioritize transactions within a finite block space. By adjusting these fees, transacting parties can influence the likelihood that their transactions will be included in the next block.

Validator participation is incentivized through various mechanisms. In PoW and PoS systems, users may offer transaction fees to compensate validators or miners for the computational and infrastructural resources expended. In PoS-based networks, validators may also receive rewards in the form of the network's native token for successfully validating or proposing a block. Moreover, staking mechanisms often allow “delegators” to contribute tokens to validator pools, receiving a proportional share of rewards in return thereby enhancing decentralization and distributing consensus power across a broader user base (Platt et al., 2021). Some networks implement “slashing” penalties to disincentivize dishonest or faulty behavior; validators that act maliciously or fail to maintain uptime risk partial or total loss of their staked assets.

In contrast, blockchain protocols based on non-incentivized consensus models, such as FBA systems (e.g., Stellar, Ripple), do not provide direct financial rewards to validators. Participation in such systems is often motivated by non-financial benefits, including enhanced control over network governance, privileged access to transaction pipelines, or strategic influence over consensus outcomes.

Given that blocks may be validated even in the absence of transactions, it is theoretically possible for validators or miners to expend significant amounts of energy without any transactional throughput. However, in systems where block rewards or transaction fees are financially meaningful, validators are economically incentivized to maximize transaction inclusion. Under such conditions, the measurement of electricity consumption per transaction becomes both methodologically sound and analytically useful, as the marginal energy cost of adding transactions tends to increase in proportion to the number of transactions processed (Lasla et al., 2022).

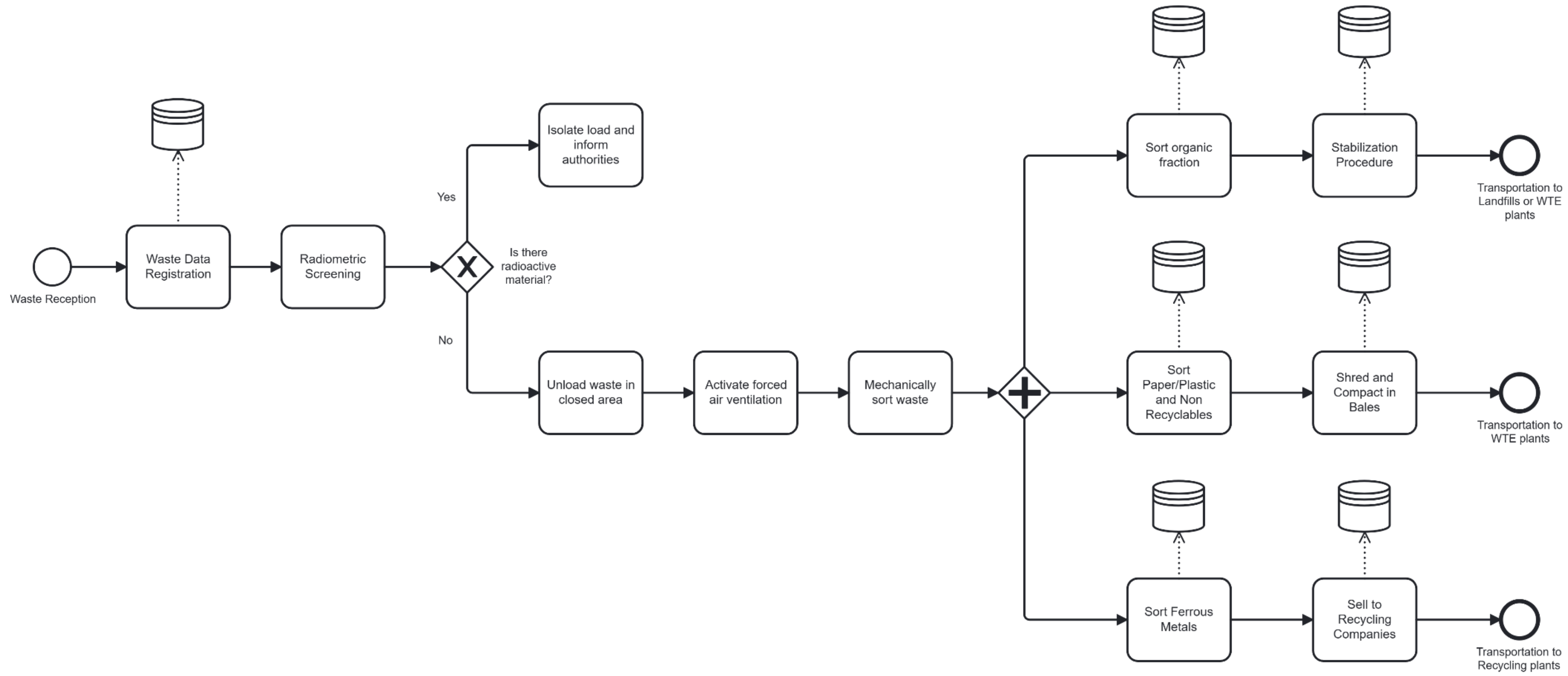
Importantly, the decentralized and pseudonymous nature of permissionless blockchain networks precludes the direct measurement of electricity usage by individual participants (Bezuidenhout et al., 2023). As a result, energy consumption must be estimated using indirect methods that are contingent on the consensus mechanism employed and the data available. Broadly, two methodological approaches are employed to estimate network-wide energy consumption, each aligned to a distinct class of consensus protocols.

For proof-of-work systems, an economic estimation model is applied. This approach infers total electricity consumption based on publicly available data such as network hashrate, mining hardware efficiency, and prevailing electricity prices. Specifically, the Cambridge Bitcoin Electricity Consumption Index (CBECI) methodology provides a structured framework for estimating both lower and upper bounds of energy usage across PoW networks (De Vries et al., 2020; Lasla et al., 2022).

In contrast, for blockchains employing alternative consensus mechanisms (e.g., PoS, FBA), a hardware-based estimation model is used. This method extrapolates network-wide electricity usage from the known or estimated energy demands of representative validator node configurations. Where direct energy measurements are unavailable, estimations are derived from the minimum hardware requirements necessary to participate in consensus operations.

While both models provide useful approximations, the robustness of these estimations varies significantly based on the precision of their underlying assumptions, the type of consensus mechanism, and the degree of network centralization or hardware standardization. Consequently, comparisons across blockchain platforms must be interpreted with caution, particularly when aggregating results derived from heterogeneous estimation methodologies.

Figure 3 - Blockchain Waste Management Process



Source: Author’s own elaboration

5.6 To-Be Process Evaluation: Environmental Cost Calculation

Assuming that non-PoW protocols are similar in the distribution of hardware and can be assessed using a common approach, the calculation of the *to-be* process environmental cost is here described using the following formula (PwC, 2022):

$E = (C + S * \beta)\ PUE + N * \gamma$

C = manufacturer-provided data on electricity consumption of piece of hardware (Wh)

S = amount of data stored (GB)

β = coefficient to estimate electricity consumption based on storage needed (Wh/GB)

PUE = power usage effectiveness if applicable, if not = 1

N = network data transmission, incoming and outgoing (GB)

γ = coefficient to estimate electricity consumption based on data transmission (Wh/GB)

Based on a recent report on blockchain sustainability (PwC, 2022), this modality of blockchain impact assessment quantifies electricity consumption across computational processes. Standardized coefficients are employed to estimate energy usage per unit of digital activity. The coefficient α, representing the electricity consumption attributable to random access memory (RAM), is estimated at 0.392 watt-hours per gigabyte (Wh/GB) (Cloud Carbon Footprint, 2024). For data storage operations, the coefficient β is substantially higher, with an estimated electricity consumption of approximately 1,200 Wh/GB (Cloud Carbon Footprint, 2024). The average power usage effectiveness (PUE) of data centers an industry-standard metric reflecting the ratio of total facility energy to IT equipment energy is taken as 1.125, consistent with global averages reported in recent assessments (Aslan et al. 2018).

The coefficient γ, corresponding to data transmission energy intensity, is estimated at 0.023 kilowatt-hours per gigabyte (kWh/GB) for inter-data center communication under typical network configurations (Carbon Footprint, 2024). However, in optimal scenarios specifically where data transmission occurs exclusively between geographically distributed data centres belonging to a single corporate entity this coefficient may be reduced significantly, approaching 0.001 kWh/GB (Aslan et al. 2018).

In the absence of real-time measurements from Intel's Running Average Power Limit (RAPL) interface or similar instrumentation, CPU power consumption can be approximated through static estimates based on utilization levels. At idle (0% utilization), CPUs are estimated to draw approximately 0.74 watts, while peak load conditions (100% utilization) may result in consumption up to 3.84 watts. These estimates provide boundary conditions for modelling CPU energy usage in systems where precise measurement tools are unavailable.

Table 16 - Concrete environmental cost drivers for PoS blockchain protocol

Parameter	Description	Unit	Data Source
CPU	Electricity consumption of CPU during node operation	kWh	Measured
RAM	Memory usage per node	Byte	Measured
α (Alpha)	Electricity consumption per gigabyte of RAM	kWh/GB	Cloud Carbon Footprint
Storage (S)	Storage usage per node	Byte	Measured
β (Beta)	Electricity consumption per terabyte of storage	kWh/TB	Cloud Carbon Footprint
PUE	Power Usage Effectiveness of data center	-	Cloud Carbon Footprint
Network Traffic (N)	Incoming and outgoing network traffic per node (converted from bit rate)	Byte	Measured
γ (Gamma)	Electricity consumption per gigabyte of network traffic	kWh/GB	Aslan et al. 2018

Source: Blockchain Sustainability Report, PwC, 2022.

Based on the data collected from secondary sources, the concrete environmental cost drivers are defined for the to-be waste management process.

TABLE 17 - CONCRETE ENVIRONMENTAL COST DRIVERS IN THE TO-BE WASTE MANAGEMENT PROCESS

Concrete Cost Driver	Functional Unit	Emission Factor (kg CO_2e)	Emission Factor (kg CO_2e)	Total Emission Factor
Diesel (Euro 6 truck), CNG truck, Electric truck (with grid mix)	per tkm	0,084	$8,4 \times 10^{-2}$	1125,084
Blockchain Data storage (See Table 14)	See Table 14	1125	$1,1\times10^{3}$	
Italian grid electricity mix, PV-sourced electricity	per kWh	0,18	$1,8 \times 10^{-1}$	0,18
Aeration system blower (kWh/day per ton)	per day-ton (12 kWh/day)	2,16	$2,16 \times 10^{0}$	4,25
Peat from EU (LCA ID: PEAT-001), shredded wood (LCA ID: WOOD-004)	per kg	0,65	$6,5 \times 10^{-1}$	
Magnetic separator energy (kWh per ton)	per ton processed (8 kWh)	1,44	$1,44 \times 10^{0}$	
Blockchain Data storage (See Table 14)	See Table 14	1125	$1,1\times10^{3}$	1125
Industrial air handler (kWh/unit of flow)	per kWh	0,18	$1,8 \times 10^{-1}$	852,18
LDPE film (per kg), compostable wrap	per kg	2	$2,0 \times 10^{0}$	
Methane (CH_4) emission factor per ton of organic material	per ton	850	$8,5 \times 10^{2}$	
Truck transport 100km (Euro 6), rail transport 200km	per 100 km (10t load)	84	$8,4 \times 10^{1}$	84

Source: Author's own elaboration based on secondary source data.

In addition to the environmental impact of blockchain waste management, evaluating the cost of a blockchain-based waste-management tracing process requires accounting for several key cost components across the waste-handling chain. Waste suppliers incur the conventional costs of collecting and transporting waste, along with the expenses associated with sorting and storing materials based on waste grade. In addition, they face blockchain-specific costs that arise from integrating and operating the digital tracking system. These include an initial fixed cost $C_{\text{fixed}}$for adopting the blockchain platform, onboarding costs expressed as a function of the onboarding parameter $C_{\text{onboarding}}$, the volume of waste handled, and the number of users U_i. Ongoing blockchain usage generates transaction costs tied to the transaction cost per unit Q_{trans}, the processed quantity, and required cloud storage CS_i. Maintenance and monitoring costs further depend on unit maintenance (C_{mc}) and monitoring (C_{mo}) rates relative to total waste processed. For this study, the blockchain cost $\hat{C}_{\text{blockchain}}$is assessed using average estimates derived from the Leeway cost estimator, acknowledging that actual figures vary with platform characteristics. Expressed as a function of processed quantity n and number of blockchain users U_j, the cost is modeled as:

$$\hat{C}_{\text{blockchain}} = n \times 20 + U_j(3 \times 0.0053 \times 43{,}800 + 3 \times 0.05 \times 250),$$

which simplifies to

$$\hat{C}_{\text{blockchain}} = 20n + 733.92U_j$$

These calculations based on the study of Gopalakrishnan (2021) can be adapted to a specific blockchain model depending on the requirements of the network users.

5.7 Scenarios and results

Two scenarios have been identified and are evaluated SOPA in the following, one representing the *as-is* process, and the second representing potential re-design for environmental impact reduction. Table 16 describes how the different environmental cost drivers are concretized in the scenario and provides their respective impact scores elicited with LCA.

The comparative results between Scenario A (traditional waste management) and Scenario B (blockchain-integrated process) reveal a marked divergence in environmental impact, particularly in the domain of digital data handling. The most prominent finding is the substantial increase in environmental cost associated with Waste Data Registration, which rises from 2.7×10^{-1} in Scenario A to 1.1×10^{3} in Scenario B. This increase is notable even though the blockchain system implemented in Scenario B was based on a Proof of Stake (PoS) consensus mechanism, specifically chosen for its comparatively lower energy consumption relative to traditional Proof of Work (PoW) protocols. Despite the use of PoS, the energy demand associated with continuous validation, network maintenance, and distributed ledger synchronization still contributes significantly to the overall environmental burden of the digital layer. In contrast, environmental cost drivers for Radiometric Screening (1.8×10^{-1}), Waste Sorting (4.25×10^{0}), Stabilization/Shredding (8.5×10^{-4}), and Selling to Recycling Companies (8.4×10^{-1}) remain constant across both scenarios, indicating that blockchain integration does not materially affect the physical processing stages. These results underscore that, while blockchain can enhance transparency, traceability, and data security in waste management, its environmental efficiency remains a concern. Future implementations must consider further optimization of blockchain infrastructure, potentially through lightweight consensus models or off-chain data solutions, to ensure that the environmental cost of digitalization does not offset its operational benefits.

Table 18 - A comparative representation of the as-is/to-be scenarios

Environmental Cost Driver	**Scenario A (*as-is*)**	**Scenario B (*to-be*)**
Waste Data Registration	$2,7 \times 10^{-1}$	$1,1 \times 10^{3}$
Radiometric Screening	$1,8 \times 10^{-1}$	See A
Waste Sorting	4,25 x 10 0	See A
Stabilization/ Shredding Procedures	$8,5 \times 10^{-4}$	See A
Waste Data Registration		$1,1 \times 10^{3}$
Selling to Recycling Companies	$8,4 \times 10^{-1}$	See A

Source: Author's own elaboration.

Chapter 6. Discussion and Conclusions

Rural waste management remains a critical and complex challenge for sustainable development. Despite growing awareness of the environmental and public health risks posed by rural solid waste, especially in non-urban areas, traditional waste management systems struggle to keep pace with increasing volumes and the unique logistical difficulties characteristic of dispersed rural settlements. This challenge is exacerbated in regions experiencing rising rural tourism, where economic benefits come hand in hand with intensified environmental pressures, underscoring the vital role of effective waste management in preserving biodiversity and sustaining the natural landscape that supports tourism.

Fragmentation within the rural waste chain spanning households, municipalities, private firms, and recyclers combined with low population density and logistical constraints, further complicates the delivery of comprehensive waste services. In Italy, these issues are compounded by inconsistent traceability and data management across regional boundaries, undermining regulatory compliance and enabling unsustainable practices such as illegal landfilling.

Although legislative frameworks like RENTRI have significantly enhanced the traceability and accountability of waste flows, challenges remain in fully realizing their potential at the rural level.

Addressing these gaps demands integrated and innovative approaches. This research contributes to the discourse by exploring a three-pillar conceptual framework that combines digital sustainability, smart village concepts, and systemic waste process modelling to improve rural waste management. The results are based on the evaluation of the waste management process impact on the environmental sustainability based on a single case study.

Waste management challenges in the Inviolata Park area mirror those commonly found in rural regions. Despite its proximity to Rome, the park's diverse and sensitive environment including wetlands, woodlands, cultivated fields, and unique geological features faces pressures similar to those in rural settings, where dispersed populations and fragmented infrastructure complicate effective waste collection and disposal. The rich biodiversity, including many rare and protected species, further elevates the importance of sustainable waste practices to prevent pollution and habitat degradation. Consequently, managing waste in this area requires approaches that address both environmental protection and logistical constraints typical of rural waste management contexts.

The waste management challenges in the Inviolata Park area, located on the eastern outskirts of Rome, reflect those commonly encountered in rural regions. Despite its proximity to an urban center, the park's rich environmental diversity with its wetlands, woodlands, cultivated fields, and unique geological formations faces pressures similar to those in dispersed rural communities, where fragmented infrastructure and logistical difficulties hinder effective waste collection and disposal. This complexity is further heightened by the presence of rare and protected species, making sustainable waste management essential to preserve the area's biodiversity.

Addressing these challenges, the present research uses the Inviolata Park as a single case study to explore innovative waste management solutions. Through the application of the SOPA methodology, this study evaluates the existing waste management processes and proposes a blockchain-enabled model tailored to balance environmental protection with the practicalities of rural waste handling.

6.1 Key Findings

This study delivers empirical insights by presenting a case of blockchain application within rural waste management systems, addressing a notable gap in the existing research. By leveraging blockchain's inherent features, such as enhanced process transparency and robust data integrity, the study demonstrates how traceability and trust in waste tracking can be significantly improved. The comparison between the *as-is* and *to-be* models reveals critical inefficiencies in current waste management practices and illustrates the potential for blockchain integration to streamline operations, reduce errors, and facilitate real-time data sharing among stakeholders. Furthermore, the environmental assessment indicates that blockchain technology can support sustainability objectives by promoting responsible waste handling and reducing unsustainable practices, although its energy consumption requires careful monitoring and management to avoid unintended negative impacts.

In response to the research questions, the findings show that blockchain technology can be both theoretically and empirically validated as a promising tool for advancing sustainable waste management (RQ1), particularly through its capabilities to enhance tracking accuracy and transaction transparency, which in turn improve operational efficiency and accountability in the sale and management of sorted waste (RQ2). However, the study also identifies several financial, infrastructural, and educational barriers that limit equitable adoption of blockchain in marginalized or resource-constrained rural communities (RQ3), including costs of technology deployment, lack of digital literacy, and limited internet connectivity. Finally, regarding environmental impacts (RQ4), while blockchain presents opportunities for more sustainable waste practices, attention must be paid to its energy footprint, advocating for the adoption of permissioned or energy-efficient consensus protocols tailored to rural contexts. Overall, these insights contribute to a nuanced understanding of blockchain's potential and challenges in fostering sustainable rural waste management.

6.2 Theoretical and Managerial Contributions

This research expands the academic conversation beyond the well-explored domain of smart cities by shifting focus to smart villages, thereby addressing a significant gap in the literature. While much of the existing academic literature emphasizes urban digital transformation and its implications for sustainability, rural areas remain underrepresented despite their unique challenges and opportunities. By adapting and applying the SOPA methodology alongside BPMN modelling specifically to a rural waste management context, this study introduces a novel use case that demonstrates how these tools can be effectively leveraged outside urban settings. This approach not only enhances understanding of rural waste processes but also provides practical frameworks for improving their efficiency and transparency. Moreover, the research bridges multiple interdisciplinary fields digital innovation, circular economy principles, and sustainability transitions highlighting their interconnectedness in the rural landscape. By integrating these perspectives, the study contributes to developing holistic strategies that support environmental sustainability in rural communities, reinforcing the potential of smart village initiatives as catalysts for sustainable development beyond urban centers.

Furthermore, the study offers several important managerial contributions that can guide practitioners, policymakers, and local authorities in addressing rural waste management challenges through digital innovation. First, it demonstrates a scalable and adaptable model that rural municipalities or protected natural areas can replicate, providing a practical blueprint for integrating blockchain into decentralized waste systems. By applying the SOPA methodology and BPMN modeling, the research equips waste management operators with a clear framework to increase operational efficiency, transparency, and data reliability key components in improving accountability and regulatory compliance. Additionally, the study supports informed policymaking by identifying actionable strategies to align waste traceability with circular economy objectives. Importantly, it advocates for the inclusion of rural digitalization in broader smart governance initiatives and the EU's green transition agenda, ensuring that smart village contexts are not left behind in sustainability efforts. These contributions collectively offer a pathway toward more equitable and effective environmental management in under-resourced or fragmented territories.

6.3 Limitations of the research

While this research offers valuable insights into the application of blockchain in rural waste management, several limitations must be acknowledged. First, the study is based on a single case study conducted in a protected natural area in the Roman province. Although the case was deliberately chosen for its relevance and complexity, the findings may not be readily generalizable to all rural contexts or waste management systems, particularly those with differing governance structures, infrastructural capacities, or socio-economic conditions. The specificity of the location, both ecologically and administratively, means that broader extrapolations should be approached with caution.

Second, the blockchain model developed in this study remains at the prototype stage. While the "to-be" process was designed following BPMN modeling and aligned with the SOPA methodological framework, it has not yet been implemented in a real-world operational setting. As such, technical, institutional, and user-related challenges that may emerge during full deployment are not fully captured. Future work should include pilot programs or live testing phases to assess the feasibility, user adoption, and technical performance of the blockchain solution in practice.

Third, the environmental impact analysis conducted here is primarily qualitative and exploratory in nature. Although the study discusses the potential for improved traceability, reduced illegal dumping, and enhanced resource recovery through blockchain integration, these benefits have not yet been verified through longitudinal or quantitative assessment. A more robust evaluation, including life cycle assessments, carbon footprint analysis, and energy consumption benchmarking, would be necessary to substantiate claims regarding the environmental sustainability of blockchain adoption.

6.4 Recommendations for Future Research

To build upon the findings of this study, future research should pursue a multi-disciplinary agenda that reinforces both the generalizability and applicability of blockchain-based waste management solutions in rural settings. Comparative and cross-contextual case studies are particularly crucial to examine how diverse regulatory environments, infrastructural capacities, and ecological conditions shape the feasibility and effectiveness of blockchain interventions. This includes cross-country comparisons within the EU or in rural economies of the Global South to assess scalability across varying levels of governance and digital maturity. Long-term evaluations of energy use and cost efficiency, especially with blockchain protocols like Proof of Stake, should be prioritized to validate environmental and economic sustainability beyond initial pilot phases. Detailed cost-benefit analyses will offer valuable insights for policymakers and practitioners assessing real-world adoption. Moreover, integrating blockchain with complementary technologies such as the Internet of Things

(IoT), Artificial Intelligence (AI), and renewable energy systems could significantly improve process automation, data granularity, and energy neutrality. From a governance perspective, future work should explore how blockchain systems align with centralized regulatory infrastructures like Italy's RENTRI and how multi-level policy coordination can facilitate equitable implementation. Finally, social dimensions must not be overlooked: research should investigate how digital literacy, infrastructure gaps, and socioeconomic disparities influence adoption in rural communities, ensuring that technological innovation supports inclusive and just sustainability transitions. These research directions are essential for consolidating blockchain's role in advancing the circular economy and smart village paradigms.

In conclusion, this thesis highlights the critical need to adapt technological innovation to the specific contexts and challenges of rural areas. While blockchain technology is often explored within urban and highly digitized environments, its potential in supporting sustainability, transparency, and effective governance in rural and ecologically sensitive regions remains largely underexamined. By applying a blockchain-based waste management model to a protected rural area and analyzing its implications through the SOPA methodology, this research provides an important contribution to rethinking digital solutions beyond the urban-centric paradigm. The findings suggest that, when thoughtfully implemented, blockchain can bridge infrastructural gaps, foster accountability, and support circular economy objectives even in resource-constrained settings. Ultimately, the thesis lays the groundwork for a more inclusive and context-sensitive digital transition in environmental governance, encouraging future innovations to reflect the diversity of geographies, communities, and ecosystems they aim to serve.

Bibliography

Abdul-Azeez, O. I. (2024). Transformational leadership in SMEs: Driving innovation, employee engagement, and business success. *World Journal of Advanced Research and Reviews*, 22(3), 1894-1905.

Adamczyk, M. B. (2019). Technology and sustainable development: Towards the future. *Entrepreneurship and Sustainability Issues*, 6(4), 2003-2016.

Adami, L. (2021). From circular economy to circular ecology: a review on the solution of environmental problems through circular waste management approaches. *Sustainability*, 13(2), 925.

Adesipo, A., Fadeyi, O., Kuca, K., Krejcar, O., Maresova, P., Selamat, A., & Adenola, M. (2020). Smart and climate-smart agricultural trends as core aspects of smart village functions. *Sensors*, *20*(21), 5977.

Adeusi, K. B. (2024). The potential of IoT to transform supply chain management through enhanced connectivity and real-time data. *World Journal of Advanced Engineering Technology and Sciences*, 12(1), 145-151.

Agovino, M. G. (2017). Institutional quality effects on separate waste collection: some evidence from Italian provinces. *Journal of Environmental Planning and Management*, 61(9), 1487-1510.

Ahl, A., Yarime, M., Tanaka, K., & Sagawa, D. (2019). Review of blockchain-based distributed energy: Implications for institutional development. *Renewable and Sustainable Energy Reviews*, *107*, 200-211.

Aid, G. E. (2017). Expanding roles for the Swedish waste management sector in inter-organizational resource management. *Resources, Conservation and Recycling*, 124, 85-97.

Aiguobarueghian, I., Adanma, U. M., Ogunbiyi, E. O., & Solomon, N. O. (2024). Waste management and circular economy: A review of sustainable practices and economic benefits. *World Journal of Advanced Research and Reviews*, *22*(2), 1708-1719.

Akkoyunlu, S. (2015). The potential of rural-urban linkages for sustainable development and trade. *International Journal of Sustainable Development & World Policy, 4*(2), 20-29.

Al Kurdi, B., Alzoubi, H. M., Akour, I., & Alshurideh, M. T. (2022). The effect of blockchain and smart inventory system on supply chain performance: Empirical evidence from retail industry. *Uncertain Supply Chain Management*, 10(4), 1111-1116.

Alam, S., Shuaib, M., Khan, W. Z., Garg, S., Kaddoum, G., Hossain, M. S., & Zikria, Y. B. (2021). Blockchain-based initiatives: Current state and challenges. *Computer Networks*, 198, 108395.

Al-Farsi, S., Rathore, M. M., & Bakiras, S. (2021). Security of blockchain-based supply chain management systems: Challenges and opportunities. *Applied Sciences, 11*(12), 5585.

Ali, J. A. (2019). Blockchain-based smart-IoT trust zone measurement architecture. In Proceedings of the International Conference on Omni-Layer Intelligent Systems, (p. pp. 152-157).

Alistair Barros, M. D. (2005). Service interaction patterns. In Proceedings of the International Conference on Business Process Management. (p. 302-318.). Springer.

Almusaed, A., Yitmen, I., Myhren, J. A., & Almssad, A. (2024). Assessing the impact of recycled building materials on environmental sustainability and energy efficiency: a comprehensive framework for reducing greenhouse gas emissions. *Buildings*, *14*(6), 1566.

Ammar, S. (2017). Enterprise systems, business process management and UK-management accounting practices: Cross-sectional case studies. *Qualitative Research in Accounting & Management,* 14(3). 230-281.

Anastasiou, E., Manika, S., Ragazou, K., & Katsios, I. (2021). Territorial and human geography challenges: How can smart villages support rural development and population inclusion? *Social Sciences*, *10*(6), 193.

Aslan, Joshua, et al. "Electricity Intensity of Internet Data Transmission: Untangling the Estimates." Wiley Online Library, 1 August 2017, https://onlinelibrary.wiley.com/doi/10.1111/jiec.12630. Accessed 1 March 2022.

Azmat, F., Lim, W. M., Moyeen, A., Voola, R., & Gupta, G. (2023). Convergence of business, innovation, and sustainability at the tipping point of the Sustainable Development Goals. *Journal of Business Research*, 167, 114170.

Babad, Y. M., & Balachandran, B. V. (1993). Cost driver optimization in activity-based costing. *Accounting review*, 563-575.

Baralla, G., Pinna, A., Tonelli, R., & Marchesi, M. (2023). Waste Management: A Comprehensive State of the Art about the Rise of Blockchain Technology. *Comput. Ind*. 2023, 145, 103812.

Barros, A., Dumas, M., & ter Hofstede, A. H. (2005, September). Service interaction patterns. In International Conference on Business Process Management (pp. 302-318). Springer.

Bartunek, J. M. (1993). Toward innovation and diversity in management research methods. *Academy of Management Journal*, 36(6), 1362-1373.

Battaglini, R., & Giordano, M. T. (2019). *Blockchain e smart contract: Funzionamento, profili giuridici e internazionali, applicazioni pratiche*. Giuffrè Francis Lefebvre.

Batubara, F. R., Ubacht, J., & Janssen, M. (2018). Challenges of blockchain technology adoption for e-government: A systematic literature review. In Proceedings of the 19th Annual International Conference on Digital Government Research.

Bertolini, P. (2019). Overview on rural poverty in developed countries. *DEMB working paper series*, 1-21.

Bertolini, P., & Pagliacci, F. (2017). Quality of life and territorial imbalances: A focus on Italian inner and rural areas.

Bertolini, P., Montanari, M., & Peragine, V. (2008). Poverty and social exclusion in rural areas. European Commission.

Bezuidenhout, R., Nel, W., & Maritz, J. M. (2023). Permissionless blockchain systems as pseudo-random number generators for decentralized consensus. *IEEE Access*, *11*, 14587-14611.

Bolton K, D. M. (2016). Resource Recovery to Approach Zero Municipal Waste. CRC Press; USA. pp 23-40.

Bonelli M, B. L. (2016). Waste prevention impacts on small municipalities: Three experiences from northern Italy. Waste Management & Research. 34(10), 1014-1025.

Bourguignon, D. (2018). EU Waste Policy: Towards a Circular Economy. European Parliamentary Research Service (EPRS). Retrieved from https://www.europarl.europa.eu/thinktank/.

Briner, R. B., Denyer, D., & Rousseau, D. M. (2009). Evidence-based management: Concept clean up time? *The Academy of Management Perspectives, 23*(4), 19-32.

Brown, L., & Osborne, S. P. (2013). Risk and innovation: Towards a framework for risk governance in public services. *Public Management Review, 15*(2), 186-208.

Bułkowska, K. Z. (2023). Implementation of Blockchain Technology in Waste Management. Energies, 16(23), 7742.

Bux, C. C. (2023). Biomethane and Compost Production by Anaerobic Digestion of Organic Waste: Suggestions for Rural Communities in Southern Italy. *Sustainability*, 15(21), 15644.

Caiado, R. G. G., Leal Filho, W., Quelhas, O. L. G., de Mattos Nascimento, D. L., & Ávila, L. V. (2018). A literature-based review on potentials and constraints in the implementation of the sustainable development goals. *Journal of cleaner production*, *198*, 1276-1288.

Calabrò, P. S., & Grosso, M. (2018). Bioplastics and waste management. *Waste Management*, *78*, 800-801.

Callan, S. J., & Thomas, J. M. (2006). Analyzing demand for disposal and recycling services: a systems approach. *Eastern Economic Journal*, *32*(2), 221-240.

Carvalho, P., & Marques, R. C. (2014). Economies of size and density in municipal solid waste recycling in Portugal. *Waste management*, *34*(1), 12-20.

Castiglione, A. C. (2023). A framework for achieving a circular economy using the blockchain technology in a sustainable waste management system. *Computers & industrial engineering*, 180, 109263.

Castiglione, A., Cimmino, L., Di Nardo, M., & Murino, T. (2023). A framework for achieving a circular economy using the blockchain technology in a sustainable waste management system. *Computers & industrial engineering*, *180*, 109263.

Castles, S. (2012). Understanding the relationship between methodology and methods. Chapters.

Cavagnaro, E. C. (2022). The three levels of sustainability. Routledge.

Cervoni Francesco, Brocchieri Davide, Crucitti Pierangelo, Grispigni Manetti Claudio, Marini Daniele, Pulvirenti Edoardo, Santoboni Leonardo. 2018. Prospetto Della Fauna Del Parco Regionale

Archeologico Naturale Dell'inviolata Di Guidonia (Roma). Associazione Nomentana Di Storia E Archeologia Onlus, Annali 2017-2018, Nuova Serie N. 17: 96-101.

Chen, G., Xu, B., Lu, M., & Chen, N.-S. (2018). Exploring blockchain technology and its potential applications for education. *Smart Learning Environments, 5*(1), 1-10.

Chesani, F. M. (2018). Compliance in business processes with incomplete information and time constraints: a general framework based on abductive reasoning. Fundamenta Informaticae, 161(1-2), 75-111.

Chioatto, E., & Sospiro, P. (2023). Transition from waste management to circular economy: the European Union roadmap. *Environ Dev Sustain*, 25, 249-276.

Chu, Z., Fan, X., Wang, W., & Huang, W. C. (2019). Quantitative evaluation of heavy metals' pollution hazards and estimation of heavy metals' environmental costs in leachate during food waste composting. *Waste Management*, *84*, 119-128.

Citroni, G., & Lippi, A. (2009). Pubblico e privato nella governance dei rifiuti in Italia. *Rivista italiana di politiche pubbliche*, *4*(1), 71-108.

Clarkson, J. E. (2010). Design process improvement: a review of current practice.

Clayton, R., Kirk, J., Banford, A., & Stamford, L. (2024). A review of radioactive waste processing and disposal from a life cycle environmental perspective. *Clean Technologies and Environmental Policy*, 1-18.

Clayton, T. &. (2018). Sustainability: a systems approach. Routledge.

Cloud Carbon Footprint. "Methodology." https://www.cloudcarbonfootprint.org/docs/methodology/.

Cohen, C. H. (2021). Trust between municipality and residents: A game-theory model for municipal solid-waste recycling efficiency. *Waste Management*, 127, 30-36.

Creswell, J. W. (2013). Steps in conducting a scholarly mixed methods study.

Cricelli, L., & Strazzullo, S. (2021). The economic aspect of digital sustainability: A systematic review. *Sustainability, 13*(15), 8241.

Davidson, S., de Filippi, P., & Potts, J. (2016). Economics of blockchain. Public Choice Conference, Fort Lauderdale, FL, USA.

Davidson, S.; de Filippi, P.; Potts, J. Economics of Blockchain; Public Choice Conference: Fort Lauderdale, FL, USA, 2016. Available online: https://hal.archives-ouvertes.fr/hal-01382002.

De Vries, A. (2020). Bitcoin's energy consumption is underestimated: A market dynamics approach. *Energy Research & Social Science*, *70*, 101721.

Decker, G., & Weske, M. (2011). Interaction-centric modeling of process choreographies. *Information Systems, 36*(2), 292-312.

Denyer, D., & Tranfield, D. (2009). Producing a systematic review. In D. A. Buchanan & A. Bryman (Eds.), *The Sage handbook of organizational research methods* (pp. 671-688). Sage.

Deslatte, A., Feiock, R. C., & Wassel, K. (2017). Urban pressures and innovations: Sustainability commitment in the face of fragmentation and inequality. *Review of Policy Research, 34*(5), 700-724.

Dewey, J. (1938). The determination of ultimate values or aims through antecedent or a priori speculation or through pragmatic or empirical inquiry. *Teachers College Record*, 39(10), 471-485.

Di Foggia, G., & Beccarello. (2021). M. Market Structure of Urban Waste Treatment and Disposal: Empirical Evidence from the Italian Industry. *Sustainability*, 13, 7412.

Dipierri, Digitalizzazione e sostenibilità: i benefici per l'Agenda 2030 di un passaggio al digitale (https://asvis.it/approfondimenti/22-5286/digitalizzazione-e-sostenibilita-i-benefici-per-lagenda-2030-di-un-passaggio-al-digitale

Division for Public Administration and Development Management Department of Economic and Social Affairs United Nations, (2016), "Compendium of Innovative Practices in Public Governance and Administration for Sustainable Development"

Domberger, S., Meadowcroft, S. A., & Thompson, D. J. (1986). Competitive tendering and efficiency: the case of refuse collection. *Fiscal studies*, *7*(4), 69-87.

Dubois, A. &. (2002). Systematic combining: an abductive approach to case research. *Journal of business research*, 55(7), 553-560.

Dubois, A. G. (2014). "Systematic combining". A decade later. Journal of Business Research, 67(6). 1277-1284.

Dumas, M. L. (2013). Fundamentals of business process management (Vol. 1, p. 2). Heidelberg: Springer.

Dumas, M., La Rosa, M., Mendling, J., & Reijers, H. A. (2018). Fundamentals of business process management (2nd ed.). Springer.

Dutta, P. K. (2019). IOT Based Waste Management System with Metering for Smart Village Project Application. *International Journal of Research Studies in Electrical and Electronics Engineering (IJRSEEE)*, *5*(1), 18-23.

Easterby-Smith, M. B. (2009). Research methods for organizational learning: The transatlantic gap. *Management Learning*, 40(4), 439-447.

Elgeddawy, M. A. (2024). Pragmatism as a research paradigm. In European Conference on Research Methodology for Business and Management Studies. Academic Conferences International Limited., pp. 71-74.

El-Haggar. (2007). Sustainable Industrial Design and Waste Management. Cradle to Cradle for Sustainable Development. Academic Press.

ENRD. (2018). Smart villages: revitalising rural services, EU Rural Review 26, availa-ble at: enrd.ec.europa.eu.

Ente Regionale RomaNatura. (n.d.). Inviolata. ParchiLazio. https://www.parchilazio.it/inviolata.

Epifani, S. (2021). Digital sustainability. Why digital transformation is the road to sustainability. Digital Transformation Institute.

Esiri, A. E. (2024). Aligning oil and gas industry practices with sustainable development goals . International Journal of Applied Research in Social Sciences, 6(6), 1215-1226.

Fernandez, A. (2013). Camunda BPM platform loan assessment process lab. Brisbane, Australia: Queensland University of Technology.

Feroz, A. K. (2021). Digital transformation and environmental sustainability: A review and research agenda. *Sustainability*, 13(3), 1530.

Finnveden, G. H. (2009). Recent developments in life cycle assessment. *Journal of environmental management*, 91(1), 1-21.

Fiorino, D. J. (2010). Sustainability as a conceptual focus for public administration. *Public Administration Review, 70*(2), 201-213.

Florin, M., & Mohammad, T. (2017). Rural Waste Management Issues at Global Level (Introductory Chapter) (June 1, 2017). Mihai FC. and Taherzadeh M J. 2017. Rural waste management issues at global level (Introductory chapter). InTech Opern. Croatia, 1-10.

França, A. S. L., Amato Neto, J., Gonçalves, R. F., & Almeida, C. M. V. B. (2020). Proposing the use of blockchain to improve the solid waste management in small municipalities. *Journal of Cleaner Production, 244*, 118639.

Frizzo-Barker, J., Chow-White, P., Adams, P., Mentanko, J., Ha, D., & Green, S. (2018). Blockchain as a disruptive technology for business: A systematic review. *International Journal of Information Management, 2*, 1-16.

García Fernández, C., & Peek, D. (2023). Connecting the smart village: a switch towards smart and sustainable rural-urban linkages in Spain. *Land*, *12*(4), 822.

Gaya, H. J. (2016). Developing a qualitative single case study in the strategic management realm: An appropriate research design. *International Journal of Business Management and Economic Research*, 7(2), 529-538.

Geiger, M. H. (2018). BPMN 2.0: The state of support and implementation. Future Generation Computer Systems, 80, 250-262.

Gerli, P. N. (2021). What makes a smart village smart? A review of the literature. Transforming Government: People, Process and Policy Vol. 16 No. 3, pp. 292-304.

Glynn, R. (2025). Nationalizing Naples in Roberto Saviano's Gomorra. In Naples and the Nation. Palgrave Macmillan, Cham.

Gnan, L., Hinna, A., Monteduro, F., & Scarozza, D. (2013). Corporate governance and management practices: Stakeholder involvement, quality and sustainability tools adoption. *Journal of Management and Governance, 17*(4), 907-937.

Gopalakrishnan, P. &. (2019). Blockchain based waste management. *International Journal of Engineering and Advanced Technology*, 8(5), 2632-2635.

Gorain, B. K. (2021). Leveraging physical, digital and knowledge connectivity for smart villages. In *Smart Villages: Bridging the Global Urban-Rural Divide* (pp. 153-175). Cham: Springer International Publishing.

Greco, S. A. (2015). Waste management in Italy and the influence of European recycling targets. *Waste Management & Research*, 33(9), 755-764.

Guanghan, S., Yujie, L., Haibo, F., Han, L., & Yang, Z. (2021). An implementation framework of blockchain-based hazardous waste transfer management system. *Environmental Science and Pollution Research, 28*(30), 42155-42170.

Habib, G., Sharma, S., Ibrahim, S., Ahmad, I., Qureshi, S., & Ishfaq, M. (2022). Blockchain technology: benefits, challenges, applications, and integration of blockchain technology with cloud computing. *Future Internet*, *14*(11), 341.

Haider, L. J. (2018). Traps and sustainable development in rural areas: a review. World Development, 101, 311-321.

Hajian, M., & Kashani, S. J. (2021). Evolution of the concept of sustainability. From Brundtland Report to sustainable development goals. In *Sustainable resource management* (pp. 1-24). Elsevier.

Halecker, B. (2015). Action case study- A research strategy based on abduction for relevant and rigorous management research. *International Journal of Business Research*, *15*(4), 23-32.

Hall, D., & Nguyen, T. A. (2012). Waste Management in Europe: Companies, Structure and Employment. Public Services International Research Unit, 36.

Hamid Damadi and Mohammadreza Namjoo, (2021), "Smart Waste Management Using Blockchain", *EEE Computer Society*

Hariram, N. P., Mekha, K. B., Suganthan, V., & Sudhakar, K. (2023). Sustainalism: An integrated socio-economic-environmental model to address sustainable development and sustainability. *Sustainability*, *15*(13), 10682.

Harvey Lieber (1970), "Public Administration and Environmental Quality", *Public Administration Review*, Vol. 30, No., pp. 277-286.

Haupt, M. V. (2017). Do we have the right performance indicators for the circular economy? insight into the Swiss waste management system. *Journal of Industrial Ecology*, 21(3), 615-627.

Hernández González, A., Calero, C., Perez Parra, D., & Mancebo, J. (2019). Approaching green BPM characterisation. *Journal of Software: Evolution and Process, 31*(2), e2145.

Homsy, G. C., & Warner, M. E. (2015). Cities and sustainability: Polycentric action and multilevel governance. *Urban Affairs Review, 51*(1), 46-73.

Howell, K. E. (2012). An introduction to the philosophy of methodology. Sage.

Hughes, L., Dwivedi, Y. K., Misra, S. K., Rana, N. P., Raghavan, V., & Akella, V. (2019). Blockchain research, practice and policy: Applications, benefits, limitations, emerging research themes and research agenda. *International Journal of Information Management, 49*, 114-129.

Hutchinson, A. M., Milke, D. L., Maisey, S., Johnson, C., Squires, J. E., Teare, G., & Estabrooks, C. A. (2010). The resident assessment instrument-minimum data set 2.0 quality indicators: a systematic review. *BMC health services research*, *10*, 1-14.

Iosifides, T. (2012). Migration research between positivistic scientism and relativism: A critical realist way out. *Handbook of research methods in migration*, 26-49.

Ishtiaq, P., Khan, S. A., & Haq, M. U. (2018). A multi-criteria decision-making approach to rank supplier selection criteria for hospital waste management: A case from Pakistan. *Waste Management & Research*, *36*(4), 386-394.

Ivona, A. R. (2021). Resilient Rural Areas and Tourism Development Paths: A Comparison of Case Studies. *Sustainability*, 13(6), 3022.

Iwuanyanwu, O. G.-O. (2024). Retrofitting existing buildings for sustainability: Challenges and innovations. *Engineering Science & Technology Journal,* 5, 2616-31.

Jansson, C. (2015). An analysis of the user perception of an interface enabling recognition and designation of waste on a line in dynamic images.

Jensen, V. V., Laursen, K., Jensen, R. H., & Smith, R. C. (2024, May). Imagining sustainable energy communities: Design narratives of future digital technologies, sites, and participation. In *Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems* (pp. 1-17).

Jiang, P., Zhang, L., You, S., Van Fan, Y., Tan, R., Klemeš, J., & You, F. (2023). Blockchain Technology Applications in Waste Management: Overview, Challenges and Opportunities. *J. Clean. Prod*., 421, 138466.

Joint SDG Fund. (2024, November 14). *Advancing the SDGs locally: Transforming communities for sustainable development*. Joint SDG Fund. https://jointsdgfund.org/article/advancing-sdgs-locally-transforming-communities-sustainable-development

Jourdaine, M., Loubet, P., Sonnemann, G., & Trébucq, S. (2021). The ABC-LCA method for the integration of activity-based costing and life cycle assessment. Business Strategy and the Environment, 30(4), 1735-1750.

Karaszewski R., Modrzynski P., Modrzynska J., (2021), "The Use of Blockchain Technology in Public Sector Entities Management: An Example of Security and Energy Efficiency in Cloud Computing Data Processing", Energies, 14, 1873. https://doi.org/10.3390/en1407187.

Katrien Steenmans, Phillip Taylor, Ine Steenmans, (2021), "Blockchain Technology for Governance of Plastic WasteManagement: Where Are We?", *Social Sciences*, 10, 434.

Kaur, P., Parashar, A. A Systematic Literature Review of Blockchain Technology for Smart Villages. *Arch Computat Methods Eng* 29, 2417–2468 (2022). https://doi.org/10.1007/s11831-021-09659-7

Kaushik, V. W. (2019). Pragmatism as a research paradigm and its implications for social work research. *Social sciences*, 8(9), 255.

Kaza, Silpa; Yao, Lisa C.; Bhada-Tata, Perinaz; Van Woerden, Frank (2018), "What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050. Urban Development", *Washington, DC: World Bank*. https://openknowledge.worldbank.org/handle/10986/30317 License: CC BY 3.0 IGO.

Kelly, L. M. (2020). Three principles of pragmatism for research on organizational processes. . Methodological innovations, 13(2), 2059799120937242.

Kesaven, B., Arularasu, M. T., Seng Hon, K., Shin Ying, F., Su Shiung, L., Keisheni, G., ... & Seeram, R. (2022). Leveraging blockchain concepts as watermarkers of plastics for sustainable waste management in progressing circular economy. *Environmental Research, 213*, 113631.

Khadke, S., Gupta, P., Rachakunta, S., Mahata, C., Dawn, S., Sharma, M., ... & Ramakrishna, S. (2021). Efficient plastic recycling and remolding circular economy using the technology of trust-blockchain. Sustainability, 13(17), 9142.

Khor, N., Arimah, B., Otieno, R., Oostrum, M. V., Mutinda, M., & Martins, J. O. (2022). *Envisaging the future of cities: World Cities Report 2022*. United Nations Human Settlements Programme (UN-Habitat).

Kim, S. C., & Quinn, R. E. (2005). *Diagnosing and changing organizational culture: Based on the competing values framework*. John Wiley & Sons.

Klessascheck, F., Weber, I., & Pufahl, L. (2025). SOPA: a framework for sustainability-oriented process analysis and re-design in business process management. *Information Systems and e-Business Management*, 1-49.

Kouhizadeh, M. &. (2018). Blockchain practices, potentials, and perspectives in greening supply chains. *Sustainability*, 10(10), 3652.

Kovács, G., & Spens, K. M. (2005). Abductive reasoning in logistics research. *International journal of physical distribution & logistics management*, *35*(2), 132-144.

Kozel, R., Podlasová, A., Šikýř, P., & Smelik, R. (2018). Innovations in waste management. *IDIMT-2018: Strategic modelling in management, economy and society: 26th interdisciplinary information management talks, Kutná Hora, Czech Republic*, 119-126.

Krajčo, K. H. (2019). The impact of new technology on sustainable development. Engineering Economics, 30(1), 41-49.

Krajnakova, M. Svazas, V. Navickas, (2019) "Biomass blockchain as a factor of energetical sustainability development", *Entrepreneurship and Sustainability Issues* 6 (3), 1456-1467.

Kumar, R. (2018). Research methodology: A step-by-step guide for beginners.

Lakhouit, A. (2025). Revolutionizing urban solid waste management with AI and IoT: a review of smart solutions for waste collection, sorting, and recycling. *Results in Engineering*, 104018.

Laouar, M. R. (2019). Towards blockchain-based urban planning: Application for waste collection management. In Proceedings of the 9th international conference on information systems and technologies , pp. 1-6.

Lasla, N., Al-Sahan, L., Abdallah, M., & Younis, M. (2022). Green-PoW: An energy-efficient blockchain Proof-of-Work consensus algorithm. *Computer Networks*, *214*, 109118.

Laureti, L., Costantiello, A., Anobile, F., Leogrande, A., & Magazzino, C. (2024). Waste Management and Innovation: Insights from Europe. Recycling, 9, 82. doi:hps://doi.org/10.3390/

Lauster, C. K. (s.d.). Literature review linking blockchain and business process management. In Proc. 15th Int. Conf. Wirtschaftsinformatik, (p. pp. 1802-1817).

Lehtinen, J., Aaltonen, K., & Rajala, R. (2019). Stakeholder management in complex product systems: Practices and rationales for engagement and disengagement. *Industrial marketing management*, *79*, 58-70.

Lieber, H. (1970). Public administration and environmental quality. Public Administration Review, 277-286.

Lillis, A. M. (2005). Cross-sectional field studies in management accounting research closing the gaps between surveys and case studies. *Journal of management accounting research*, 17(1), 119-141.

Lorino, P. (2018). Pragmatism and organization studies. Oxford University Press.

Lu, Y. (2019). The blockchain: State-of-the-art and research challenges. *Journal of Industrial Information Integration*, 15, 80-90.

M.A. Hannan, M. A. (2015). A review on technologies and their usage in solid waste monitoring and management systems: Issues and challenges. *Waste Management*, 509-523.

Maiurova, A. K. (2022). Promoting digital transformation in waste collection service and waste recycling in Moscow (Russia): Applying a circular economy paradigm to mitigate climate change impacts on the environment. *Journal of Cleaner Production*, 354, 131604.

Marques, R. C., Simões, P., & Pinto, F. S. (2018). Tariff regulation in the waste sector: An unavoidable future. *Waste management*, *78*, 292-300.

Maxwell, J. A. (2010). Realism as a stance for mixed methods research. *SAGE handbook of mixed methods in social & behavioral research*, 2, 145-168.

Mazzanti, M., & Zoboli, R. (2008). Waste generation, waste disposal and policy effectiveness: Evidence on decoupling from the European Union. *Resources, conservation and recycling*, *52*(10), 1221-1234.

Meironke, A. S. (2019). Business process compliance and blockchain: How does the ethereum blockchain address challenges of business process compliance? 14th International Conference on Wirtschaftsinformatik. Germany.

Mendling, J. W. (2018). Blockchains for business process management-challenges and opportunities. ACM Transactions on Management Information Systems (TMIS), 9(1), 1-16.

Merriam, S. B., & Tisdell, E. J. (2009). Dealing with validity, reliability, and ethics. Qualitative research: A guide to design and implementation, 209-235.

Mersico, L. A. (2025). Exploring the role of digital platforms in promoting value co-creation: evidence from the Italian municipal solid waste management system. Sustainability Accounting, Management and Policy Journal, Ahead of Print.

Mihai, F. C. (2017). Solid waste management in rural areas. oD-Books on Demand.

Mihai, F. C. (2018). Waste collection in rural communities: Challenges under EU regulations. A case study of Neamt County, Romania. *Journal of Material Cycles and Waste Management*, 20, 1337-1347.

Mike Marin, R. H. (2012). Data centric BPM and the emerging case management standard: A short survey. *Business Process Management Workshops*, Revised Papers. (p. 24-30). Springer.

Miller, D. C. (2002). Handbook of research design and social measurement. Sage.

Milutinovic, M. H. (2016). Proof of luck: An efficient blockchain consensus protocol. In proceedings of the 1st Workshop on System Software for Trusted Execution, (p. pp. 1-6.).

Mohanty, S., Mohanta, B., Nanda, P., Sen, S., & Patnaik, S. (2020). Smart village initiatives: an overview. *Smart village technology: concepts and developments*, 3-24.

Mondejar, Maria E., Ram Avtar, Heyker Lellani Baños Diaz, Rama Kant Dubey, Jesús Esteban, Abigail Gómez-Morales, Brett Hallam et al. "Digitalization to achieve sustainable development goals: Steps towards a Smart Green Planet." *Science of The Total Environment* 794 (2021): 148539.

Mougayar, W. (2016). *The business blockchain: promise, practice, and application of the next Internet technology*. John Wiley & Sons.

Musella, G. A. (2019). Evaluating waste collection management: the case of macro-areas and municipalities in Italy. *Environment, Development and Sustainability*, 21, 2857-2889.

Naldi, L. N. (2015). What is smart rural development? *Journal of rural studies*, 40, 90-101.

Nayeri, S. S. (2025). Towards waste management 5.0: A nexus between circular economy and industry 5.0 dimensions. *Waste Management*, 203, 114830.

Nikolova, A. V. (2024). COMPARATIVE ANALYSIS OF BPMN TOOLS. *Balkan Journal of Applied Mathematics and Informatics*, 7(2), 61-70.

Nofer M., Gomber P., Hinz O., Schiereck D., (2017), "Blockchain", *Bus inf Syst Eng*, 59(3), 183-187.

OECD. (2024). Economic Instruments for the Circular Economy in Italy. 219.

OECD. (2024, April 26). Digital technologies for better enforcement of waste regulation and elimination of waste crime. (OECD Environment Working Papers No. ENV/WKP(2024). OECD Publishing.

Offenhuber, D. (2023). *Waste is information: infrastructure legibility and governance*. MIT Press.Eisenhardt, K. M. (1989). Building theories from case study research. *Academy of management review*, *14*(4), 532-550.

Olanrewaju, O. I. (2024). Driving energy transition through financial innovation: The critical role of Big Data and ESG metrics. *Computer Science & IT Research Journal*, 5(6), 1434-1452.

Onukwulu, E. C.-U. (2024). Advances in blockchain integration for transparent renewable energy supply chains. *International Journal of Research and Innovation in Applied Science*, 9(12), 688-714.

Passarini, F. V. (2011). Indicators of waste management efficiency related to different territorial conditions. *Waste management*, 31(4), 785-792.

Patwa, A. P. (2020). Solid waste characterization and treatment technologies in rural areas: An Indian and international review. Environmental Technology & Innovation, 20 , 101066.

Paul, S., Choudhury, M., Deb, U., Pegu, R., Das, S., & Bhattacharya, S. S. (2019). Assessing the ecological impacts of ageing on hazard potential of solid waste landfills: A green approach through vermitechnology. *Journal of Cleaner Production*, 236, 117643.

Pedersen, A. B. (2019). A ten-step decision path to determine when to use blockchain technologies. MIS quarterly executive, 18(2), 99-115.

Penzenstadler, B. &. (2013). A generic model for sustainability with process-and product-specific instances. In Proceedings of the 2013 workshop on Green in/by software engineering, pp. 3-8.

Piras, F. P. (2025). The Impact of Socio-Economic Factors on the Development of Rural Tourism: Italian Case Based on a Regional Analysis. *Tourism and Hospitality*, 6(1), 3.

Platt, M., Sedlmeir, J., Platt, D., Xu, J., Tasca, P., Vadgama, N., & Ibañez, J. I. (2021, December). The energy footprint of blockchain consensus mechanisms beyond proof-of-work. In *2021 IEEE 21st International Conference on Software Quality, Reliability and Security Companion (QRS-C)* (pp. 1135-1144). IEEE.

Podgaiskyte. (2014). Waste management sector value changes in Lithuania along the last decade. Proc Soc Behav Sci 110; Contemporary Issues in Business, Management and Education 2013, 512-519.

Pomberger, R. S. (2017). Dynamic visualisation of municipal waste management performance in the EU using Ternary Diagram method. *Waste management*, 61, 558-571.

Pongrácz, E., & Pohjola, V. J. (2004). Re-defining waste, the concept of ownership and the role of waste management. *Resources, conservation and Recycling*, *40*(2), 141-153.

Popkova, E. G. (2022). Economics of climate change: Global trends, country specifics and digital perspectives of climate action. *Frontiers in Environmental Economics*, 1, 935368.

Prybila, C. S. (2017). Runtime verification for business processes utilizing the bitcoin blockchain. CoRR.

Ranieri, E., Rada, E. C., Ragazzi, M., Masi, S., & Montanaro, C. (2014). Critical analysis of the integration of residual municipal solid waste incineration and selective collection in two Italian tourist areas. *Waste management & research*, *32*(6), 551-555.

Reichert, M. W. (2012). Enabling flexibility in process-aware information systems: challenges, methods, technologies. Heidelberg: Springer. (Vol. 54).

Renukappa, S., Suresh, S., Abdalla, W., Shetty, N., Yabbati, N., & Hiremath, R. (2024). Evaluation of smart village strategies and challenges. *Smart and Sustainable Built Environment*, *13*(6), 1386-1407.

Rouse, J. (2018). Engaging science: How to understand its practices philosophically. Cornell University Press.

Rukhiran, M., Boonsong, S., & Netinant, P. (2024). Sustainable optimizing performance and energy efficiency in proof of work blockchain: A multilinear regression approach. *Sustainability*, *16*(4), 1519.

Santos, T., Almeida, J., Silvestre, J. D., & Faria, P. (2021). Life cycle assessment of mortars: A review on technical potential and drawbacks. *Construction and Building Materials*, *288*, 123069.

Sarantakos, S. (2005). Social Research. Melbourne: Macmillan Education. (3rd ed.).

Sastre, S., Llopart, J., & Ventosa, I. P. (2018). Mind the gap: A model for the EU recycling target applied to the Spanish regions. *Waste Management*, *79*, 415-427.

Saunders, M. L. (2003). Research Methods for Business Students (3rd ed.). England: Prentice Hall.

Seadon, J. K. (2010). Sustainable waste management systems. *Journal of cleaner production*, 18(16-17), 1639-1651.

Sedlmeir, J., Buhl, H. U., Fridgen, G., & Keller, R. (2020). The energy consumption of blockchain technology: Beyond myth. *Business & Information Systems Engineering*, *62*(6), 599-608.

Shleifer, A. &. (1997). A survey of corporate governance. The journal of finance, 52(2), 737-783.

Sileyew, K. J. (2019). Research design and methodology (Vol. 7, 2). London: Cyberspace.

Simões, P., & Marques, R. C. (2012). On the economic performance of the waste sector. A literature review. *Journal of environmental management*, *106*, 40-47.

Škoda, M. (2009). The importance of ABC models in cost management. OF THE UNIVERSITY OF PETROŞANI~ ECONOMICS~, 9(2), 263-274.

Slee, B. (2019). Delivering on the concept of smart villages-in search of an enabling theory. European countryside, 11(4), 634-650.

Sohns, T. M. (2023). Green business process management for business sustainability: A case study of manufacturing small and medium-sized enterprises (SMEs) from Germany. Journal of Cleaner Production, 401, 136667.

Somwanshi, R., Shindepatil, U., Tule, D., Mankar, A., Ingle, N., Rajamanya, G. B. D. V., & Deshmukh, A. (2016). Study and development of village as a smart village. *International Journal of Scientific & Engineering Research*, *7*(6), 395-408.

Sorooshian, S. (2024). The sustainable development goals of the United Nations: A comparative midterm research review. *Journal of Cleaner Production*, 142272.

Sparviero, S. &. (2021). Towards digital sustainability: The long journey to the sustainable development goals 2030. *Digital Policy, Regulation and Governance*, 23(3), 216-228.

Stake, R. (1995). Case study research. Springer.

Stevens, B. J. (1978). Scale, market structure, and the cost of refuse collection. *The review of economics and statistics*, 438-448.

Storbacka, K. (2011). A solution business model: Capabilities and management practices for integrated solutions. *Industrial Marketing Management*, 40(5), 699-711.

Strzelecka, C. (2024). Critical data studies meets discard studies: Waste data reflectivity in digital urban waste tracking system. *Convergence*, *30*(6), 2109-2130.

Subanda, I. N., & Dewi, N. L. Y. (2023, May). Smart Village Development Efforts Based on Communication Strategy Formulation and Policy Advocacy. In *International Conference on Business and Technology* (pp. 430-436). Cham: Springer Nature Switzerland.

Sun, D., Hao, L., & Xie, D. (2024). Governance of rural solid waste under a multi-subject governance model. *Scientific Reports*, *14*(1), 27111.

Sutriadi, R. (2018, November). Defining smart city, smart region, smart village, and technopolis as an innovative concept in indonesia's urban and regional development themes to reach sustainability. In *IOP Conference Series: Earth and Environmental Science* (Vol. 202, p. 012047). IOP Publishing.

Swami, V., Chamorro-Premuzic, T., Snelgar, R., & Furnham, A. (2011). Personality, individual differences, and demographic antecedents of self-reported household waste management behaviours. *Journal of Environmental Psychology*, *31*(1), 21-26.

Taelman, S. E., Tonini, D., Wandl, A., & Dewulf, J. (2018). A holistic sustainability framework for waste management in European cities: Concept development. *Sustainability*, *10*(7), 2184.

Taherdoost, H. M. (2024). Decision making: Models, processes, technique. Cloud Computing and Data Science, , 1-14.

Taskinsoy, J. (2019). Global cooling through blockchain to avoid catastrophic climate changes by 2050. *Available at SSRN 3495674*.

Taylor, P. J. (2020). A systematic literature review of blockchain cyber security. *Digital Communications and Networks*, 6(2), 147-156.

Teddlie, C. &. (2010). Overview of contemporary issues in mixed methods research. Sage handbook of mixed methods in social and behavioral research, 2, 1-44.

Terre Blanche, M. D. (1999). Histories of the present: Social science research in context. Research in practice: Applied methods for the social sciences, 2(1), 1-7.

Tosida, E. T., Herdiyeni, Y. E. N. I., & SUPREHATIN, R. M. (2024). Spatial-based Smart Community Infrastructures Model of smart economy sustainability in smart village environment. *Journal of Sustainability Science and Management*, *19*(2), 279-299.

Tsang, E. W. (2013). Case study methodology: Causal explanation, contextualization, and theorizing. *Journal of international management*, 19(2), 195-202.

Tubertini, C., & De Donno, M. (2020). Frammentazione comunale e contrasto allo spopolamento: la prospettiva italiana. *LE ISTITUZIONI DEL FEDERALISMO*, *2*, 297-321.

Van Der Aalst, W. M. (2016). Business process management: Don't forget to improve the process! Business & Information Systems Engineering, 58(1), 1-6.

Van Maanen, J. S. (2007). The interplay between theory and method. *Academy of management review*, 32(4), 1145-1154.

Vanwersch, R. J. (2016). A critical evaluation and framework of business process improvement methods. *Business & Information Systems Engineering*, 58, 43-53.

Viriyasitavat, W., Da Xu, L., Niyato, D., Bi, Z., & Hoonsopon, D. (2022). Applications of blockchain in business processes: A comprehensive review. *Ieee Access*, *10*, 118900-118925.

Visvizi, A., & Lytras, M. D. (2018). It's not a fad: Smart cities and smart villages research in European and global contexts. *Sustainability*, 10(8), 2727.

Vom Brocke, J. R. (2010). Handbook on business process management (Vol. 2). Heidelberg: Springer.

Wang, D. H. (2020). Life cycle assessment of municipal solid waste management in Nottingham, England: Past and future perspectives. *Journal of cleaner production*, 251, 119636.

Wilson, F. P. (2013). Business models for people, planet (& profits): exploring the phenomena of social business, a market-based approach to social value creation. Small business economics, 40, 715-737.

Xiao, Y., Zhang, N., Lou, W., & Hou, Y. T. (2020). A survey of distributed consensus protocols for blockchain networks. *IEEE communications surveys & tutorials*, *22*(2), 1432-1465.

Yannick. (2016). CORK 2.0 DECLARATION 2016. A Better Life in Rural Areas. L. E. O. N. A. R. D.

Yin, R. (2003). Case Study Research: Design and Methods.

Yvonne Feilzer, M. (2010). Doing mixed methods research pragmatically: Implications for the rediscovery of pragmatism as a research paradigm. *Journal of mixed methods research*, 4(1), 6-16.

Zaccariello, L. C. (2015). Evaluation of municipal solid waste management performance by material flow analysis: Theoretical approach and case study. . Waste Management & Research, 33(10), 871-885.

Zavratnik, V. K. (2018). Smart villages: Comprehensive review of initiatives and practices. Sustainability, 10(7), 2559.

Zhang, Y. G. (2025). Synergizing Blockchain and Internet of Things for Enhancing Efficiency and Waste Reduction in Sustainable Food Management. Trends in Food Science & Technology, 104873.

Zuhaira, B. A. (2021). Business process modelling, implementation, analysis, and management: the case of business process management tools. Business Process Management Journal, 27(1), 145-183.