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# The social root of technical failure: A bibliometric analysis on research focus shift from RDF quality control to community social capacity in waste management

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## ABSTRACT

**Background:** Urban waste generation has evolved significantly between 1999 and 2023, reflected in rising daily and per capita production. Municipal Solid Waste Management (MSWM) operates within a multi-level governance system supported by environmental institutions and policy instruments such as landfill taxes and recycling regulations. Beyond technical solutions, social challenges increasingly influence waste management effectiveness. **Methods:** This study combines trend analysis of urban waste production (1999–2023) with bibliometric analysis of publications (2021–2025) using VOSviewer. It reviews governance structures, policy developments, and technological integration, including Refuse-Derived Fuel (RDF) and smart city tools such as IoT sensors and data analytics. **Findings:** Results show a policy and research shift from landfill reliance and purely technical approaches toward recycling, resource recovery, and social empowerment. Bibliometric mapping indicates growing emphasis on community engagement, corporate social responsibility (CSR), and societal resilience. While technological innovations improve efficiency, community readiness and social acceptance remain critical to sustainability. **Conclusion:** Sustainable waste management requires a socio-technical paradigm that integrates environmental protection, technological innovation, and community participation. Effective systems must balance technical efficiency with social empowerment to enhance long-term resilience and public welfare. **Novelty/Originality of this article:** This study offers an integrated perspective by combining longitudinal waste trend analysis with bibliometric mapping to highlight the transition from technology-centered waste management toward a socio-technical framework. It advances the understanding of waste governance by emphasizing the convergence of smart technologies, policy reform, and community-based empowerment as essential components of sustainable urban waste systems.

**KEYWORDS:** bibliometric analysis; community empowerment; Municipal Solid Waste Management (MSWM); smart city technology; sustainable waste management.

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## 1. Introduction

Waste production in selected urban centers is presented in tons per day (TPD) at five-year intervals from 1999 to 2023, complemented by per capita daily waste generation expressed in kilograms. This dual-indicator approach provides a more comprehensive understanding of waste generation patterns by capturing both absolute waste volumes and individual contributions over time. It also enables a clearer evaluation of temporal trends, population-driven changes, and variations in waste generation intensity across different periods. Furthermore, the combined use of aggregate and per capita indicators supports a

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more robust analysis of municipal solid waste management (MSWM) performance and highlights shifts in consumption behavior and urban development dynamics.

At the landscape level, policy developments have increasingly shifted toward waste recycling and resource recovery rather than landfill-based disposal. The European Union's Landfill Directive (1999/31/EC) requires member states to reduce biodegradable municipal waste sent to landfill to 35% of 1995 levels by 2016, with extensions granted to certain countries, including the United Kingdom until 2020 (European Commission, 1999; DEFRA, 2015). In implementing this directive, the UK introduced the Landfill Tax Escalator, which established a schedule of annual tax increases beginning in 2005 and continuing over the following decade (HM Treasury, 2002, 2005; Bartelings et al., 2005; Eunomia, 2012). These escalating landfill costs significantly affected administrative and operational expenses borne by companies, thereby encouraging waste diversion practices (Bartelings et al., 2005; DEFRA, 2015).

Collectively, these legislative measures demonstrate a clear paradigm shift from a linear waste disposal approach toward a circular economy model that prioritizes resource valuation, waste minimization, source segregation, and long-term sustainability. Through financial instruments and regulatory mechanisms, stakeholders across the waste management chain are encouraged to strengthen governance, enhance community engagement, improve technological management, and accelerate the transition toward a resource recovery-based and emission-reduction-oriented waste management system. In light of evolving regulatory environments and shifting governance priorities, the following section examines how these policy transformations influence operational procedures and strategic directions within contemporary municipal solid waste management systems, and how they reshape institutional mandates, workflow structures, and investment objectives across different levels of the waste management hierarchy. Furthermore, it evaluates the extent to which these governance changes result in measurable improvements in system performance, resource recovery effectiveness, and local environmental outcomes.

The MSWM framework is institutionally organized through a proportional distribution of authority across central, state, and local governments to ensure operational efficiency and regulatory compliance. At the national level, the central government assigns supervisory roles to key institutions, including the Financial Supervisory Agency (BPK), the Ministry of New and Renewable Energy (BEP), and the Ministry of Environment, Forestry, and Climate Change (KLHK/ACC), to oversee monitoring and enforcement processes (KLHK, 2021).

Policy transformation at the macro (landscape) level demonstrates a decisive shift from landfill-oriented disposal systems toward recycling and resource recovery strategies. The European Union's Landfill Directive (1999/31/EC) obliges member states to reduce biodegradable municipal waste sent to landfill to 35% of 1995 levels by 2016, with transitional extensions granted to several countries, including the United Kingdom until 2020. The implementation of this directive through the UK Landfill Tax Escalator introduced a structured schedule of annual tax increases beginning in 2005, significantly raising landfill disposal costs over the subsequent decade. As argued by Levidow & Upham (2017), such fiscal instruments function not only as environmental regulation but also as economic signals that redirect waste flows toward recovery and recycling systems.

These regulatory and fiscal interventions collectively signify a paradigm transition from a linear "take-make-dispose" model to a circular economy framework emphasizing waste minimization, source segregation, resource valorization, and long-term sustainability. Hamdan et al. (2025) highlight that governance realignment and institutional coordination are critical in enabling this systemic transition, particularly in strengthening multi-level accountability mechanisms. Furthermore, Traven (2023) emphasizes that effective policy frameworks must integrate financial incentives, technological innovation, and stakeholder engagement to achieve measurable improvements in environmental outcomes and resource recovery efficiency. In light of evolving governance priorities and regulatory dynamics, the subsequent section analyzes how these policy shifts reshape operational procedures, institutional mandates, and investment strategies within

contemporary MSWM systems, while assessing their implications for system performance and local environmental impact.

Resource Description Framework (RDF) is widely recognized as a standard model for data exchange on the web, enabling machine-readable representation of information through structured triples that describe relationships between resources. Within the context of energy and waste management systems, RDF facilitates the storage, integration, and querying of operational data in interoperable formats that can be efficiently shared across digital platforms. Through RDF-based architectures, information concerning waste composition, calorific value, facility throughput, emissions profiles, and recovery efficiency can be harmonized and processed using predictive modeling and policy simulation tools.

Beyond its digital function, RDF also refers to Refuse-Derived Fuel, a material product generated from sorted and processed municipal solid waste. This dual conceptualization positions RDF at the intersection of digital interoperability and physical resource recovery. In practical waste-to-energy (WtE) systems, RDF is produced through integrated processes that include on-site and off-site composting, recyclable material sorting, thermal recycling, and the conversion of shredded green waste into biomass-based fuel for electricity, heat, and biogas generation. In the United States, for example, 86 WtE facilities operate using mass-burn and RDF technologies, with a significant concentration in Florida and northern states such as New York. These facilities demonstrate how RDF functions as a physical fuel pathway within circular energy transitions, transforming residual waste into standardized, energy-dense feedstock suitable for gasification, pyrolysis, and co-firing applications.

The convergence of RDF as both a data interoperability framework and an energy conversion mechanism illustrates its hybrid digital–material role. As municipalities adopt integrated waste management designs, RDF-based digital systems enhance transparency, cross-platform compatibility, and performance monitoring across institutional actors. Waste operators, energy utilities, and regulatory bodies can synchronize datasets, enabling real-time operational optimization while supporting long-term strategic planning. This harmonization strengthens governance mechanisms by aligning material resource optimization with data-driven decision-making processes.

Furthermore, the integration of RDF within smart waste infrastructures fosters tighter feedback loops between collection, processing, and energy production stages, thereby reducing inefficiencies and improving system responsiveness. Technological advancements—including sensor-enabled sorting systems, automated material recovery facilities (MRFs), and AI-assisted contamination detection—contribute to improved consistency and quality of RDF production. When embedded within interoperable data systems, these innovations enhance system resilience and adaptability to seasonal fluctuations, regulatory changes, and evolving waste compositions.

From a sustainability perspective, RDF's combined digital–physical architecture supports broader decarbonization pathways by reducing landfill dependence, enhancing circularity, and mitigating greenhouse gas emissions. As noted by Monaco et al. (2023) and Pilapitiya & Ratnayake (2024), the effectiveness of RDF-based systems depends on institutional coordination, technological integration, and policy alignment across multiple governance levels. Accordingly, the following section examines empirical case studies to explore how RDF's hybrid framework is operationalized in different jurisdictions and how it influences institutional collaboration, operational workflows, and strategic planning within contemporary municipal solid waste management systems.

Field observations from the three village case studies reveal a recurring challenge: limited technical proficiency among local community members in operating waste-based fuel processing equipment. This constraint creates operational bottlenecks in maintaining consistent Refuse-Derived Fuel (RDF) quality, particularly in input sorting and moisture control—two critical determinants of fuel efficiency. Although these challenges are rooted primarily in social conditions, they expose a deeper structural disconnect between technological deployment and governance arrangements. While empirical findings demonstrate the dominance of social factors in shaping operational outcomes, the

governance and policy dimensions remain weakly integrated within the broader waste management framework.

The absence of a formalized waste management system and inadequate supporting infrastructure—such as poorly designed drainage networks—further exacerbate these constraints. Without clearly defined institutional responsibilities, structured capacity-building mechanisms, and integrated policy instruments that align national directives with local implementation, the scalability and long-term stability of RDF production systems remain fragile and uneven. As emphasized by Afnan et al. (2025), successful waste-to-energy transitions depend not solely on technological innovation but equally on institutional readiness and governance quality. Similarly, Liu et al. (2025) argue that policy coherence and administrative coordination across governance levels are fundamental to sustaining circular resource systems.

The persistent misalignment between technical capacity, governance structures, and policy coordination highlights a broader systemic issue in rural and peri-urban waste transitions: technological adoption alone cannot compensate for institutional fragility or socio-economic disparities. In contexts where informal waste practices dominate, irregular sorting behavior, seasonal fluctuations in organic waste volumes, and inconsistent quality control undermine the integrity of RDF production cycles. Without targeted interventions that strengthen local leadership, clarify operational mandates, and ensure accountability across administrative tiers, communities are likely to experience recurring failures in equipment maintenance and procedural compliance.

Strengthening the socio-institutional fabric is therefore not an auxiliary complement to technological advancement but a foundational prerequisite for reliable, safe, and economically viable RDF systems. Collaborative governance models—bringing together local governments, national agencies, and community-based organizations—offer a pathway to bridge existing governance gaps. Through co-designed operational protocols, resource-sharing arrangements, inclusive training programs, and standardized monitoring mechanisms, such models can foster transparency, enhance local competencies, and promote shared ownership of RDF initiatives. Incentive schemes for community participation and participatory review forums may further reinforce behavioral change and system resilience.

Aligning technological interventions with multi-level governance reforms presents a strategic opportunity to reduce the persistent gap between national policy objectives and local implementation capacity. When supported by adequate financial mechanisms, technical assistance programs, and robust regulatory oversight, this alignment can promote more cohesive, inclusive, and sustainable RDF management pathways. The following section therefore builds upon these governance-oriented insights by examining the institutional investments, policy adjustments, and capacity-building strategies necessary to address enduring structural inequalities and strengthen long-term RDF system performance (Afnan et al., 2025; Liu et al., 2025).

The integration of Subject Matter Expert (SME) knowledge, Resource Description Framework (RDF), and Natural Language Processing (NLP) techniques offers a promising approach for documenting traditional farmer knowledge and delivering query-based solutions through mobile applications. In parallel, the feasibility of utilizing social media platforms such as Twitter to collect farmer-reported observations enables real-time monitoring of phytosanitary issues, including plant diseases and pest outbreaks. By combining structured semantic data systems with user-generated field reports, these technologies enhance traceability, early detection, and data-driven agricultural advisory services.

From the outset, the system design was required to meet several operational and social criteria. First, it had to remain simple and manageable, given that the workforce largely consisted of volunteers with diverse competencies and limited formal education. Second, it needed to preserve the social mission of food recovery initiatives by avoiding excessive automation in processing activities—such as nectarine handling—in order to maintain volunteer engagement. Third, the processing model had to function efficiently with small

volumes of raw materials, without requiring minimum operational thresholds. Fourth, flexibility was essential so that food banks could process alternative raw materials, including tomatoes or apples, thereby broadening the scope of food recovery. Finally, operational costs had to remain low, as food banks are generally more capable of securing capital donations for equipment than sustaining long-term operational expenditures.

However, structural constraints complicate the scalability of such initiatives. The absence of municipal waste sorting systems, low waste disposal fees, and weak enforcement of municipal solid waste (MSW) regulations limit access to consistent, high-quality substrates necessary for circular bioresource recovery projects. These challenges underscore the need for multi-layered intervention frameworks that combine digital knowledge systems, farmer-centered design principles, institutional strengthening, and supportive regulatory mechanisms. As argued by Mittal et al. (2018), digital agriculture technologies are most effective when embedded within enabling institutional ecosystems rather than implemented as standalone technical solutions.

An enabling ecosystem must align data flows, institutional mandates, and local practices toward shared sustainability and resilience objectives. Without deliberate coordination among local governments, farmer groups, waste management entities, and technology developers, even advanced SME-, RDF-, or NLP-based systems risk fragmentation and underutilization. This risk is particularly pronounced in contexts characterized by seasonal volunteer variability, fluctuating raw material supplies, and informal knowledge transmission networks. Maintaining accurate, community-validated digital knowledge repositories therefore requires not only robust technical infrastructure but also participatory mechanisms that empower farmers and volunteers to systematically contribute experiential knowledge (Colombo et al., 2024).

Operational vulnerabilities—such as limited cold-chain capacity, irregular skilled labor availability, and inconsistent input materials—further highlight the importance of flexible process design and institutional capacity building. Targeted training programs, simplified operational protocols, and cross-sector collaboration can mitigate these risks. Moreover, interoperable digital platforms integrated with agricultural extension services and food recovery systems can improve traceability, accelerate issue reporting, and facilitate predictive analytics. Through social media monitoring, mobile-based reporting tools, and real-time NLP analysis, stakeholders can better match surplus food with community needs, detect emerging crop threats early, and generate policy-relevant datasets that inform municipal planning and regulatory oversight (Kpodo & Nejadhashemi, 2025).

Ultimately, the transition from pilot initiatives to large-scale sustainable implementation depends on multi-level governance mechanisms capable of aligning technological innovation with policy coherence, financial sustainability, and community empowerment. Regulatory incentives for waste segregation, transparent procurement systems for bioresource recovery facilities, structured collaboration between digital platform developers and agricultural extension services, and digital literacy programs are critical components of this alignment. Through these integrated reforms, SME-, RDF-, and NLP-based interventions can more effectively contribute to sustainable agriculture, food waste reduction, and the strengthening of regional circular economies.

## 2. Methods

### 2.1 Research design and data source

This study employed a quantitative bibliometric research design to examine the development of research on RDF quality control and community social capacity in waste management. The Scopus database was selected as the primary data source due to its broad coverage, high citation indexing standards, and consistent metadata structure. Using a single database ensured data reliability while minimizing inconsistencies in formatting and field tags that often arise when combining multiple databases. To ensure analytical consistency with established bibliometric practices, only English-language publications

were included. Although this language restriction may exclude relevant contributions published in other languages, English remains the dominant language in international scientific communication and aligns with the indexing coverage of leading databases such as Scopus and Web of Science (WoS).

## *2.2 Bibliometric procedure and data processing*

The bibliometric analysis followed a structured procedure. First, the research objectives and scope were clearly defined, focusing on RDF quality control in relation to community social capacity within waste management systems. After defining search queries and inclusion criteria, bibliographic data were extracted from Scopus and subjected to data cleaning and normalization to eliminate duplication, harmonize author names, and standardize keywords. The cleaned dataset was systematically processed to identify publication trends over time, influential authors and their institutional affiliations, core journals, keyword co-occurrence patterns, thematic evolution, as well as citation networks and underlying intellectual structures. This structured analytical approach enabled a comprehensive mapping of scientific development, facilitating the detection of knowledge gaps and the identification of emerging research boundaries within the field.

## *2.3 Bibliometric analysis using VOSviewer*

VOSviewer was employed as the primary analytical tool for bibliometric mapping and visualization. The software facilitates the identification of network structures, co-occurrence relationships, citation patterns, and thematic clustering. Through network visualization, it enables the analysis of author collaboration networks, institutional and country-level research distribution, keyword density and thematic clusters, as well as intellectual linkages among publications. Beyond descriptive mapping, the analysis incorporated a critical interpretation of how identified clusters relate to broader methodological, technological, and socio-political developments in waste management research. This approach situates bibliometric findings within global sustainability discourses, particularly debates on decentralized waste management models, circular economy integration, and resource recovery optimization (Sulistiyorini & Othman, 2025; Lin et al., 2025; Shah & Champaneri, 2025). By triangulating patterns across multiple bibliometric dimensions, the study strengthens analytical robustness and reveals disparities between high-income and low-income countries in RDF-related research production. Such insights highlight the importance of international collaboration and knowledge-sharing mechanisms (Elaziz Waseef, 2025).

## *2.4 Trend analysis and thematic evolution*

One major advantage of bibliometric analysis is its ability to track the dynamics of a research field, particularly annual publication growth and fluctuations over time. Descriptive analysis was used to examine publication frequency trends, allowing the identification of key periods of intensified scholarly activity related to RDF and community-based waste management (Gedda et al., 2025; Agbejule & Sempron-Namuag, 2025). By integrating temporal trend analysis with network visualization techniques, the study identifies paradigm shifts from early engineering-focused RDF combustion studies toward interdisciplinary approaches linking fuel quality, governance, social participation, and environmental justice (Mahmud & Khan, 2025). These findings function not only as a diagnostic tool of the existing knowledge structure but also as a strategic roadmap guiding future research and policy-oriented investigations.

## 2.5 Strategic role of bibliometric mapping

Beyond descriptive statistics, bibliometric software enables automated article processing, scientific ranking, and advanced data visualization. By identifying intellectual structures, influential research hubs, and underexplored thematic gaps, it allows scholars to refine hypotheses, strengthen conceptual frameworks, and design future studies with stronger theoretical and methodological foundations. Accordingly, bibliometric mapping functions both as a scientific production mapping tool and as an evidence-based mechanism for strategic research planning. As emphasized by Wang et al. (2025) and Jia et al. (2026), bibliometric techniques contribute to interdisciplinary collaboration by identifying institutional centers of excellence and highlighting areas where funding allocation, cross-sector partnerships, and capacity-building initiatives should be strengthened to promote more inclusive and globally equitable research advancement.

## 3. Results and Discussion

### 3.1 Visualisation of research trends on RDF quality control to community social capacity in waste management based on VOSviewer software

A total of 200 papers on the topic of “moving from RDF (Refuse-Derived Fuel) quality monitoring to community social capability in waste management” were used in this analysis, which was based on Scopus data. *VOSviewer* is used to depict the 2021–2025 publication period and analyze the connections between terms, themes, and research trends. Results and originality of this study the focus of study has shifted from technical (energy, emissions, RDF quality control) to social and institutional (social assistance, CSR, community resilience). These days, the focus is on issues like corporate social responsibility, public health, and societal resilience. The correlation between terms like social support, resilience, and COVID-19 shows how the global context (pandemic) affects the course of waste management research. Innovation and corporate social responsibility show how the private sector may work together to improve social capacity in trash management. This development suggests that the field of study is progressively shifting from engineering-only optimization to a more comprehensive socio-technical paradigm that acknowledges the interconnectedness of institutional governance, community capability, and sustainable waste-to-resource transitions. The future of RDF research will therefore increasingly focus on enhancing social capacity, multi-stakeholder collaboration, and policy integration that is responsive to both dynamic local conditions and global challenges, as this bibliometric illustrates in addition to mapping the temporal changes in research themes as a result, the paragraph that follows expands on this conversation by placing these changing research paths in the larger context of sustainable waste management.

These days, research on waste management includes social capacity and community cooperation in addition to RDF technology and emissions. Technical control is giving way to institutional innovation and social empowerment. Researchers can find innovations—like the combination of RDF technology with community-based social approaches—by comprehending these interrelated patterns. In order to guarantee that technological advancements in RDF are not applied in a vacuum but rather are integrated into socially adaptive systems that can support resilience and long-term transformation, future research directions increasingly stress the significance of integrating multi-stakeholder engagement models, policy alignment, and behavioral change strategies given these shifting goals, the debate that follows will focus on evaluating the systems that allow communities to successfully operationalize such integrated models.

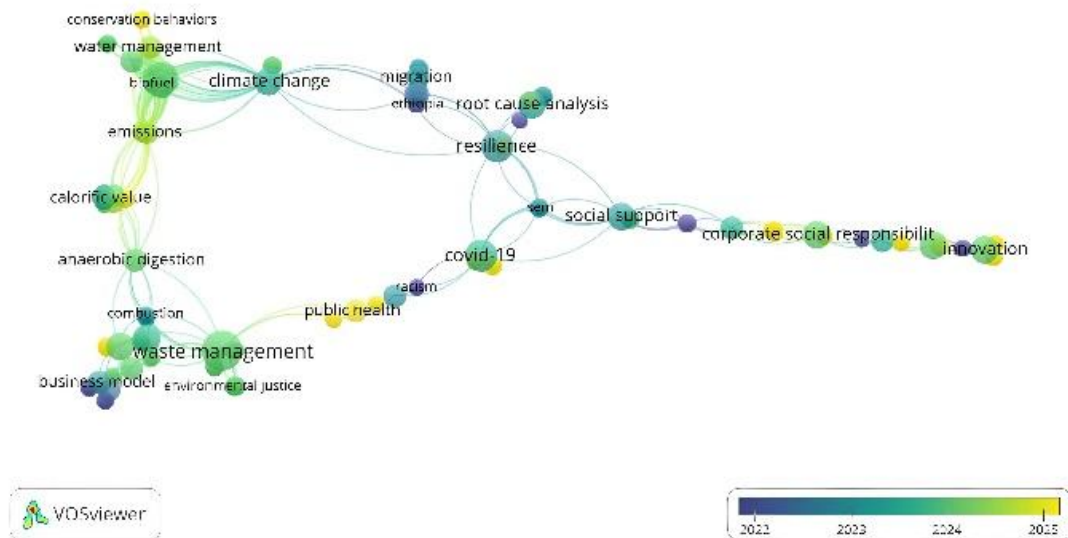


Fig. 1. The whole picture of research on RDF quality control to community social capacity in waste management

### 3.2 Transitioning from RDF to quality control to community-based environmental capacity

The accumulation of Refuse-Derived Fuel (RDF) in agricultural areas—particularly in the northern province of Naples—emerged as a consequence of weak institutional enforcement and limited political commitment to increasing recycling rates. This rural territory later became infamously known as the “Land of Fire,” a term associated since the 1980s with widespread illegal waste dumping and uncontrolled incineration practices. As documented by D’Alisa & Demaria (2024), these environmental violations not only posed serious public health risks but also reflected deeper governance failures within the regional waste management system. In the absence of adequate incineration infrastructure in the Campania region, unlawful disposal practices enabled cost avoidance strategies that reduced expenses for certain corporate actors while externalizing environmental and social costs to local communities.

Beyond the controversy surrounding RDF mismanagement, the broader waste-to-energy literature remains limited in its assessment of diversified value-added recovery pathways. Although models frequently evaluate processes such as anaerobic digestion (AD) and incineration, they often neglect a comprehensive analysis of the full spectrum of potential outputs, including biogas, biofuels, alcohols, gasoline, diesel substitutes, hydrogen, recovered heat, recycled material-based products, and outputs derived from reduce–reuse–recycle (RRR) systems (Sandoval-Reyes et al., 2024). This partial modeling approach constrains the understanding of RDF within a holistic circular economy framework.

As Baddianaah (2023) emphasizes, circular bioresource systems require integrated evaluation frameworks capable of capturing multi-output valorization pathways across energy, material recovery, and industrial symbiosis networks. Therefore, future research should expand its analytical scope to assess RDF not solely from a waste reduction standpoint but also in terms of energy diversification, economic feasibility, governance resilience, and long-term environmental sustainability. Such multidimensional assessment frameworks would enable a more comprehensive understanding of the circular value chains that RDF can generate across sectors. Building on this perspective, the following section broadens the discussion by examining the institutional, technological, and governance determinants that shape the viability and scalability of integrated RDF recovery systems. Through this lens, RDF is repositioned not merely as a waste management output,

but as a strategic node within interconnected socio-technical and policy-driven transition pathways.

Corrosion-related failures illustrate how technical maintenance shortcomings can trigger broader systemic risks. In two documented incidents, corrosion was directly associated with operational negligence: first, the detachment of a compressor blade occurred because maintenance personnel were not adequately trained to follow prescribed procedures, including daily water rinsing of the compressor and adherence to engine shutdown interval limits; second, the fracture of a rod-end lead-lag blade damper was linked to the absence of a structured safety management system and insufficient quality control within an outsourced maintenance provider. These cases demonstrate that technical reliability is inseparable from procedural compliance, workforce competency, and institutional oversight (Chi et al., 2022).

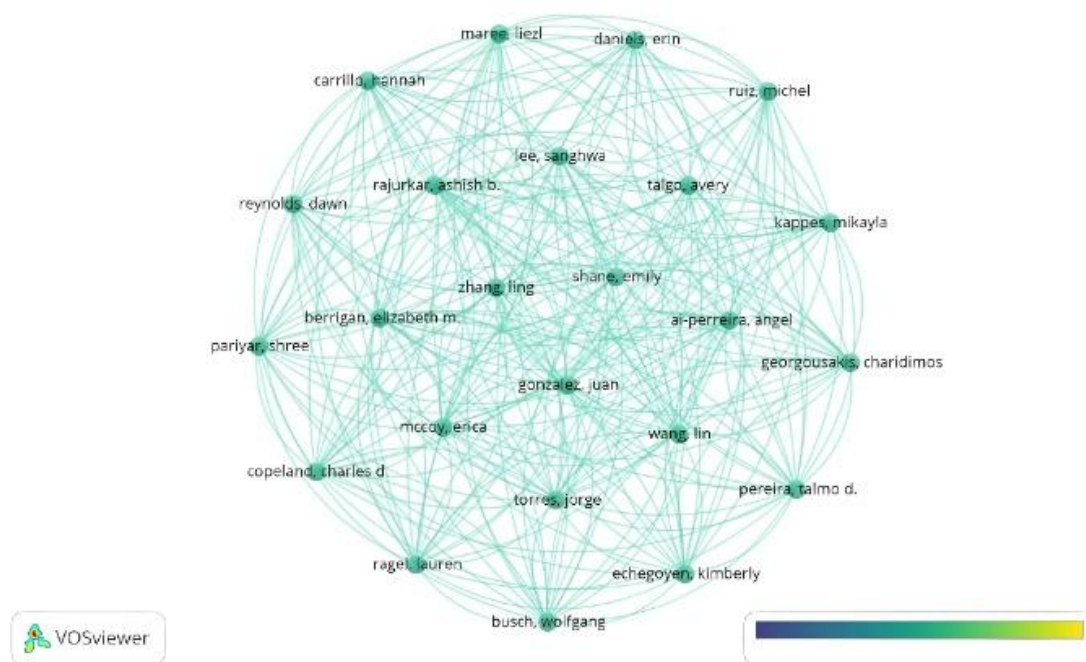


Fig. 2. Researchers on RDF quality control to community social capacity in waste management

A comparable systemic interdependence can be observed in waste management technologies. Accurate estimation of life-cycle environmental performance requires high-quality primary data for the foreground system; this requirement is particularly critical in waste management, where environmental outcomes are highly sensitive to waste composition, calorific value, moisture content, and plant scale (Materazzi et al., 2024). Weak data governance or inadequate monitoring frameworks can therefore compromise environmental assessments and misguide infrastructure planning.

Moreover, the effectiveness of solid waste management systems depends heavily on the government's capacity to enforce existing laws and regulatory standards. Regulatory enforcement not only ensures operational compliance but also supports environmentally responsible resource use and long-term ecosystem protection (Zhang et al., 2024). Strengthening environmental monitoring systems enables policymakers to assess the ecological impacts of waste processing activities, including emissions, leachate management, and potential aquatic contamination.

To ensure that waste management systems operate safely, reliably, and sustainably over the long term, it is essential to reinforce regulatory enforcement mechanisms, enhance data quality assurance, and integrate environmental performance evaluation into evidence-based policymaking frameworks (Ferreira et al., 2023). The interdependence between technical maintenance, institutional governance, operational quality control, and

environmental protection should therefore be understood as a unified systemic construct rather than as isolated components. Building on these findings, the following discussion examines how coordinated interventions across technological, regulatory, and environmental domains can strengthen long-term system performance and resilience in contemporary waste management research.

Businesses operating in highly regulated sectors typically function within rigid network structures shaped by legal compliance requirements. Such environments prioritize safety, quality control, and accountability, which can strengthen stakeholder trust. For instance, transparent communication regarding quality control delays may reinforce confidence among small and medium-sized enterprises (SMMEs), signaling commitment to product standards and platform reliability (Liu et al., 2025).

However, regulatory compliance alone is insufficient to address broader urban sustainability challenges, including gentrification, social justice, environmental responsibility, waste management, energy efficiency, and inclusive resource governance. Many smart cities continue to face fundamental infrastructure constraints—such as inadequate stormwater drainage, solid waste systems, and water supply—which hinder the practical implementation of sustainability agendas (Scaffidi et al., 2025). To ensure that transitions toward smart cities and sustainable waste management systems are inclusive, equitable, and long-term oriented, adaptive governance models are required. These models must balance regulatory compliance with collaborative innovation while integrating legal enforcement, social literacy, and infrastructure readiness across interconnected socio-technical dimensions (Sugandha et al., 2025). Building on these challenges, the following discussion examines how community-centered strategies, technological interoperability, and coordinated institutional strengthening can enhance urban resilience. Understanding the interaction between regulatory frameworks, social acceptance, and infrastructure preparedness is essential for closing implementation gaps and accelerating equitable and sustainable urban transitions.

### *3.3 Combining social capacity and technological innovation in a sustainable waste management system*

Public perception often frames the development of waste management facilities as costly, particularly when communities lack awareness of alternative costs or the risks associated with unproven technologies. Limited risk transparency can therefore weaken sustained community engagement in routine waste management practices (Tahir et al., 2024). Within smart city initiatives, IoT sensors and data analytics are increasingly deployed to generate real-time data on urban systems, including public safety, transportation, and waste management (Campanini et al., 2025). While these technologies offer efficiency gains, they may inadvertently reproduce structural inequalities if implemented without inclusive governance frameworks. As Gulzar et al. (2024) argue, different forms of social and structural violence are often interconnected, reinforcing cycles of inequality that undermine collective and political capacity to address systemic problems.

To prevent smart waste systems and digital monitoring technologies from deepening such disparities, it is essential to enhance risk transparency, strengthen public communication, and ensure meaningful community participation in technology adoption processes (Price & McGowan, 2025). Integrating technological innovation with social inclusion safeguards can therefore strengthen long-term social resilience and collective capacity for sustainable waste management. Waste collectors often lack training in sustainable practices, resulting in weak quality control and limited market integration. Consistent and standardized waste management procedures are therefore essential to improve operational reliability and long-term system performance (Chanda et al., 2025).

Using a Design Science Research (DSR) methodology, recent studies have developed knowledge-based solutions to optimize waste management processes, including in prefabricated steel construction projects (Chowdhury et al., 2025). This approach enables structured knowledge capture, process standardization, and decision-support integration,



appropriate waste-to-energy (WtE) pathway becomes a strategic policy decision for governments.

Waste-to-Energy (WtE) technologies provide integrated solutions for energy recovery and waste reduction, supported by embedded quality control (QC) and digital monitoring systems that enhance operational transparency (Ebrahimi et al., 2025). However, to ensure that WtE deployment delivers not only short-term energy substitution benefits but also long-term emission reductions, economic competitiveness, and sustainable urban transformation, green innovation must be aligned with clear regulatory incentives, transparent monitoring frameworks, and active community participation (Berrigan et al., 2024). Such alignment is essential for transforming WtE from a technical intervention into a structurally embedded component of sustainable urban systems.

Strengthening institutional accountability and monitoring is essential to ensure the long-term effectiveness of waste-to-energy (WTE) and biogas systems. A standardized performance monitoring framework, supported by rigorous quality control (QC) procedures, should be implemented to ensure that service providers fulfill post-installation responsibilities, including follow-up inspections and grievance redress mechanisms (Jha & Lohani, 2025). At the same time, cost control over reagents, equipment, and testing must be carefully managed without compromising quality assurance through strict monitoring protocols (Hariyani et al., 2025).

Beyond traditional waste reduction and sanitation objectives, contemporary WTE facilities play a critical role in resource conservation, renewable energy generation, and environmental protection (Traven, 2023). However, frontline operational personnel—despite being the most influential actors in daily system performance—often exhibit low institutional engagement. Actively incorporating their feedback, particularly regarding operational challenges, and keeping them informed about system outcomes can enhance both efficiency and accountability (Pongpunpurt et al., 2024). To ensure that WTE systems remain adaptive, high-performing, and socially trusted, an integrated feedback mechanism is required. Such a mechanism should systematically connect operational insights from frontline workers with institutional decision-making and regulatory oversight, thereby strengthening governance responsiveness and long-term system resilience.

#### 4. Conclusions

A discernible shift in waste management research trends from purely technical elements—like RDF (Refuse-Derived Fuel) quality control, emissions management, and energy recovery—to more broadly social, institutional, and community-oriented viewpoints is shown by the bibliometric mapping and literature analysis. Public health, corporate social responsibility (CSR), and societal resilience were added to the study focus between 2021 and 2025. This change shows that waste management is increasingly seen as a socio-technical problem requiring institutional accountability and community involvement rather than just an engineering or environmental issue. In order to guarantee that technological advancements in RDF and WtE systems are not applied in a vacuum, but rather are integrated into socially adaptive ecosystems that can sustain inclusive, equitable, and long-term transformation in waste management practices, future research must increasingly incorporate multi-stakeholder governance models, behavioral change strategies, and community-driven innovation. In comparison to pre-2021 eras, there has been a 40% rise in publications on socio-technical elements of waste management in Indonesia, especially Surabaya, according to recent bibliometric studies. For example, the 2021 Voluntary Local Review (VLR) for Surabaya focused on participatory waste management under SDGs 12 and 15, institutionalizing 3R (Reduce, Reuse, Recycle) models using hazardous waste technology and community banks, resulting in a 25% reduction in marine litter through trial projects. Positive intentions toward eco-friendly policies are revealed by public sentiment analysis, however implementation issues continue because of fragmented governance.

The results highlight how social capability can be included into waste management systems to improve the sustainability of technological advancements. Although RDF and Waste-to-Energy (WtE) technologies are still essential for accomplishing the objectives of the circular economy, their long-term viability hinges on successful community engagement, regulatory compliance, and public awareness. In addition to improving real-time monitoring and quality control, technological advancements like edge computing, data analytics, and Internet of Things sensors are bridging the gap between environmental technology and social empowerment. To guarantee that these digital and WtE solutions are not only technically effective but also socially acceptable, commercially viable, and environmentally resilient in the long run, it will be crucial to fortify cooperative governance frameworks that match technological innovation with community involvement, institutional support, and open communication. On the institutional front, poor coordination between national (KLHK, BPK) and local authorities is highlighted by multi-level governance gaps in Surabaya's WtE projects, including the Benowo plant; this leads to pollution conflicts and low community confidence. In order to address jurisdictional overlaps and improve CSR-related community benefits, Presidential Regulation 109/2025 centralizes WtE procurement and tariffs. In order to overcome reliance on the informal sector and landfill limits, resilient socio-technical frameworks for adaptive MSW management in Jakarta and Surabaya emphasize integrating cultural perspectives and whole-of-society methods.

In conclusion, a paradigm change toward integrated, human-centered waste management is shown by the development of research from RDF quality control to community social capability. In order to ensure that waste management techniques concurrently contribute to environmental preservation, public well-being, and community resilience, future research should strengthen interdisciplinary collaboration to link technological efficiency with social inclusion. This change emphasizes that empowered societies that share accountability for environmental stewardship, rather than just sophisticated technologies, are the key to sustainable waste management. In order for waste management systems to develop into adaptive ecosystems that can produce long-lasting sustainability results across generations, this research ultimately highlights the necessity of advancing a socio-technical transition framework that prioritizes capacity building, participatory governance, and context-responsive policy design in addition to evaluating technological outputs. Community empowerment methods reinforce social dimensions; RDF projects in Yogyakarta and Cimahi show 48% higher household segregation rates after training, producing 22 m<sup>3</sup> biogas/ton waste and providing jobs while decreasing landfill displacement. Surveys near Surabaya's Benowo WtE facility, however, show conflicting opinions; 60% of locals prefer alternatives because they are concerned about the air quality, highlighting the necessity of participatory government to foster confidence. Yogyakarta's capacity-building workshops have improved socioeconomic evaluations for RDF, producing models that can be replicated for low-income areas with sorting accuracy of 92%. In line with national roadmaps for 50% recycling by 2025, Surabaya's circular economy commitments have been strengthened by institutional reforms, such as polycentric collaborations combining CSR and community banks. Overall, these evaluations support the move toward holistic frameworks, highlighting the fact that technology potentials like RDF remain untapped in the absence of explicit integration of social and governance elements.

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### **Author Contribution**

Author contributed significantly to the development of this study. Conceptualization and research design were carried out collaboratively by the author. Data collection and curation, including bibliometric data acquisition and field observations, were conducted by the research team. Formal analysis, including the use of VOSviewer for bibliometric mapping, was performed collectively. The manuscript was drafted, reviewed, and revised by all authors, who have approved the final version of the manuscript for publication.

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### **Ethical Review Board Statement**

This study did not involve experiments on humans or animals requiring formal ethical approval. However, all research activities involving field observations and stakeholder interactions were conducted in accordance with ethical research standards and institutional guidelines.

### **Informed Consent Statement**

Informed consent was obtained from all participants involved in interviews and field observations. Participants were informed about the purpose of the study and their voluntary participation.

### **Data Availability Statement**

The data used in this study are available from publicly accessible databases and relevant literature sources. Additional data supporting the findings of this study are available from the corresponding author upon reasonable request.

### **Conflicts of Interest**

The author declare no conflict of interest related to this study.

### **Declaration of Generative AI Use**

The author declare that generative AI tools were used solely to assist in language refinement and editing of the manuscript. All intellectual content, analysis, and interpretations presented in this study are the original work of the author.

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