

Electronic waste in the European Union: A systematic review and a pathway for sustainable management

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ABSTRACT

Electronic waste (e-waste) remains among the fastest-growing and difficult waste streams to manage. It poses serious environmental and public-health risks when improperly handled. While the European Union (EU) has established a comprehensive regulatory framework—centred on the Waste Electrical and Electronic Equipment (WEEE) and Restriction of Hazardous Substances (RoHS) Directives—implementation outcomes continue to vary widely among member states. This review examines how e-waste governance operates across the EU through a systematic literature review (SLR) of 138 peer-reviewed publications published between 2002 and 2025 and indexed in Scopus and Web of Science. The findings show that EU e-waste governance is anchored in extended producer responsibility but remains concentrated on end-of-life management (e.g., reuse, repair, remanufacturing, recycling, and safe disposal) while upstream actions such as eco-design and sustainable production are underdeveloped. The barriers often identified are regulatory, operational, and behavioural, including uneven enforcement, informal waste flows, high collection costs, weak incentives for repair and reuse, and limited public participation. The study provides a novel and practical pathway comprising four interconnected pillars—governance, economic, social, and technological—that together strengthen the coherence and sustainability of e-waste management in the EU.

1. Introduction

Electronic waste (e-waste) poses significant environmental and health risks when improperly handled (Rautela et al., 2021). Effective management depends not only on technical capacity but also on coherent systems of governance that align environmental, economic, and social objectives (Xavier et al., 2023; Gaur et al., 2024). Despite sustained policy attention, e-waste remains one of the fastest-growing waste streams worldwide and continues to challenge governments and industries alike (Baldé et al., 2024; Shittu et al., 2021). The complexity of e-waste management stems from its cross-cutting nature: it spans multiple policy domains, involves a wide range of actors, and requires coordination across production, consumption, and disposal (Andeobu et al., 2021a; Brindhadevi et al., 2023; Jain et al., 2023). These characteristics make it an important case for understanding how governance systems address collective environmental problems in an era of globalised production and trade.

This study examines the governance of e-waste in the European

Union (EU).¹ The EU has developed one of the world's most comprehensive regulatory frameworks for e-waste, centred on the Waste Electrical and Electronic Equipment (WEEE) and Restriction of Hazardous Substances (RoHS) Directives, and reinforced by later initiatives under the Circular Economy (CE) Action Plan and the European Green Deal. These measures aim to improve collection, recycling and recovery rates, and to restrict the use of hazardous materials in production (European Union, 2011, 2012). Yet documented formal collection and recycling rates remain below 50 per cent (42.8%), large volumes of e-waste continue to leave formal management systems, and national performance varies markedly across the region (Shittu et al., 2021; Maes and Preston-Whyte, 2022; Traverso et al., 2024; Baldé et al., 2024).

Several studies have examined these challenges in depth. Parajuly et al. (2020) and Andeobu et al. (2021a) note that many member states struggle to implement EU directives effectively. While countries such as Sweden, Germany and France have established robust collection systems and advanced circular-economy initiatives, others—including Romania and Cyprus—continue to face institutional and

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¹ The United Kingdom is included in the dataset due to its participation in EU waste-management frameworks for most of the review period (2002–2025) and the continued alignment of its legislation with EU directives.

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infrastructural constraints (Constantinescu et al., 2022). Intermediate cases, such as Italy and Ireland, demonstrate progress through regulatory reforms; however, Europe more broadly continues to engage in transboundary trade under the classification of used electronics (Favot and Grasseti, 2017; McMahon et al., 2021; Zacho et al., 2018). Together, these patterns illustrate the diversity of national experiences and the continuing need to understand how e-waste governance operates across the EU (Constantinescu et al., 2022; Gaur et al., 2024).

Previous research has offered valuable insights into specific aspects of this system, such as collection and recycling (Constantinescu et al., 2022; Neves et al., 2024b; Nikou and Sardianou, 2023), responsible consumption (Parajuly et al., 2020; Pirvu et al., 2023) and extended producer responsibility (EPR) (Vernier, 2021; Compagnoni, 2022; Compagnoni et al., 2025). However, existing studies do not sufficiently incorporate socioeconomic, governance, and behavioural factors (Xavier et al., 2023; Gaur et al., 2024). Our study addresses that gap by conducting a systematic literature review (SLR) of e-waste governance in the EU, bringing together evidence that is currently dispersed across disciplinary and thematic boundaries, and providing a pathway for strengthening the coherence and sustainability of e-waste management in the region.

The review draws on 138 peer-reviewed articles published between 2002 and 2025 and indexed in Scopus and Web of Science. It follows recognised standards for systematic research, applying the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework and the approach proposed by Tranfield et al. (2003) to ensure transparency and replicability. The analysis focuses on four central themes: (1) the governance frameworks that structure e-waste management, (2) the dominant management practices observed across EU member states, (3) the barriers that constrain effective and sustainable management, and (4) the key strategies for sustainable management.

The results show that e-waste governance in the EU is built around EPR, operationalised through the WEEE and RoHS Directives. In practice, management activities centre on reuse, repair, remanufacturing, recycling, and safe disposal, while strategies aimed at influencing product design and consumption remain limited. The most frequently identified barriers fall into three categories—regulatory, operational, and behavioural—including inconsistent enforcement, informal waste flows, high collection costs, weak incentives for reuse and repair, and limited public participation.

Overall, the literature portrays a system that is ambitious in design but uneven in implementation. The challenge lies less in the absence of policy than in aligning regulations, operational capacity, and behavioural change. Building on these findings, this review brings together proposals from the literature into four interconnected pillars of sustainable management—governance and regulatory frameworks, economic and financial mechanisms, social dimensions, and technical and design innovations—and uses these to develop a pathway for advancing e-waste governance in the EU.

The remainder of the paper is structured as follows. Section 2 describes the review methods. Section 3 presents the main findings on governance frameworks, management practices, barriers to implementation, and key strategies for sustainable management. Section 4 builds on these results to propose an integrated four-pillar approach to sustainable management and its implications for policy and research. Section 5 concludes the study and identifies areas for future research.

2. Materials and methods

The SLR approach is widely recognised as an effective method for synthesising research in the field of e-waste and environmental governance (e.g. Maphosa and Maphosa, 2020; Anandh et al., 2021; Pan et al., 2022; Ni et al., 2023; Lee et al., 2024; Owonikoko and Alimba, 2024). To ensure methodological rigour, transparency, and replicability, this SLR followed the guidelines proposed by Tranfield et al. (2003), which

outline a structured and transparent process encompassing three stages: planning, conducting, and reporting the review.

2.1. Planning the review

The planning stage began with a scoping exercise to identify how e-waste governance has been studied across disciplines such as engineering, social science and geography. This helped to determine the scope of the review and refine the search strategy. Previous SLRs on e-waste and environmental management (e.g., Ikhlaiel, 2018; Andeobu et al., 2021a; Binner et al., 2023; Gaur et al., 2024) provided methodological guidance for defining search terms, inclusion criteria, and relevant databases. Although these studies differed in focus, their approaches informed the design of this review.

The search strategy targeted research on e-waste in the EU, including studies published between 2002 and 2025.² Search terms combined three dimensions: (1) e-waste, (2) policy and governance, and (3) the European region. Keywords for ‘policy and governance’ were selected for precision and breadth— ‘police*’ captured policy and policies, ‘politic*’ retrieved politics and political, and ‘governance’ identified studies explicitly examining governing structures and processes. Together, these criteria produced a comprehensive dataset of EU e-waste research covering regulatory frameworks, management practices, barriers to implementation, and proposals for sustainable governance (Table 1).

2.2. Conducting the review

In the second stage, the PRISMA framework was applied to further improve the transparency, replicability, and reporting quality of the review (Liberati et al., 2009; Page et al., 2021). Based on the keywords identified during the planning stage, a search string was constructed using Boolean operators (“AND” and “OR”).³ This string was applied

Table 1
Criteria to identify relevant publications in the Scopus and WoS databases.

Criteria or keywords	Search term
E-waste	e-waste", electr* waste, waste electrical and electronic equipment, WEEE
Policy and governance	police*, politic*, "governance"
Geographic region	Europe*, EU, Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, United Kingdom, UK, Britain, England, Scotland, Wales

[*] represent wildcards that were used to broaden the search

² The geographical scope of this review was defined to include the EU and the United Kingdom (UK). Although the UK formally exited the EU in 2020, it was included due to its participation in the waste management frameworks in the region (European Union, 2012; Council of the EU and the European Council, 2023). The EU, when used in this SLR, therefore refers to all the 27 member states and the UK, also referred to as EU27+UK (see for instance, Mazzarano (2022)).

³ ("e-waste" OR electr* waste OR "waste electrical and electronic equipment" OR "WEEE") AND (police* OR politic* OR "governance") AND (Europe* OR "EU" OR "Austria" OR "Belgium" OR "Bulgaria" OR "Croatia" OR "Cyprus" OR "Czech Republic" OR "Denmark" OR "Estonia" OR "Finland" OR "France" OR "Germany" OR "Greece" OR "Hungary" OR "Ireland" OR "Italy" OR "Latvia" OR "Lithuania" OR "Luxembourg" OR "Malta" OR "Netherlands" OR "Poland" OR "Portugal" OR "Romania" OR "Slovakia" OR "Slovenia" OR "Spain" OR "Sweden" OR "United Kingdom" OR "UK" OR "Britain" OR "England" OR "Scotland" OR "Wales")

across the “All fields” option in Scopus and Web of Science databases to ensure maximum coverage of the literature.⁴ The search results were refined using several inclusion criteria: publication year (2002–2025), document type (articles, review articles, books, book chapters, and proceedings papers), language (English), and subject category (Environmental and Social Sciences).

The year 2002 was selected as the starting point due to the introduction of the WEEE Directive 2002/96/EC (European Union, 2003). English was selected as the language filter due to time constraints, and was applied as an eligibility criterion to allow English-language articles to be captured (Pieper and Puljak, 2021). The selection of Environment and Social Sciences as the primary subject areas reflected the interdisciplinary nature of the study, which examines e-waste management through environmental, social, behavioural, governance, and policy perspectives (Davis and Wolski, 2009; Bridgens et al., 2019). This restriction further enabled the search to be refined in accordance with the study objectives, thereby improving the relevance and focus of the literature to be included in the review.

From this search, a total of 1723 articles were retrieved and exported into Rayyan platform, a web application recognised for its role in systematic research (Ouzzani et al., 2016; Quevedo et al., 2025). The platform assisted authors to collaboratively decide on which articles to include in the SLR by screening the title and abstract of the publications (Olofsson et al., 2017; dos Reis et al., 2023). Following the PRISMA protocols, 294 duplicates were removed. Screening was restricted to studies addressing e-waste management from a social science perspective and with substantive relevance to the EU27+UK context, resulting in the exclusion of 630 articles. The remaining 799 articles underwent further quality assessment through detailed manual review of their abstracts and conclusions by the authors, facilitated through Rayyan. This resulted in the exclusion of 560 articles that were either insufficiently aligned with the research objectives or lacked substantial analysis of e-waste governance and management relevant to the review.

The remaining 239 articles underwent full-text assessment to determine their substantive relevance to the research objectives, and contribution to understanding e-waste governance and management. References of articles were also searched manually to identify additional relevant sources not captured in the electronic search. Ultimately, a total of 138 articles were included in the SLR (Fig. 1).

Although systematic procedures were applied throughout the screening and selection process, certain limitations are acknowledged. The exclusion of studies based on titles, abstracts, and conclusions may have resulted in the omission of potentially relevant articles where substantive contributions were not immediately apparent at these stages. Similarly, assessments of alignment with the research objectives and relevance to e-waste governance within the EU27+UK context involved an element of interpretive judgement, which may introduce selection bias despite efforts to maintain consistency. To mitigate these limitations, article selection was conducted iteratively using Rayyan, with screening decisions informed by detailed reviews of titles, abstracts, conclusions, and subsequently full texts. In addition, multiple authors participated in the screening process, and manual searching of reference lists was undertaken to identify influential studies not captured through the initial electronic searches. While these measures cannot entirely eliminate the possibility of excluding relevant literature, they were intended to enhance the transparency, consistency, and robustness of the review process.

2.3. Reporting and dissemination

The selected articles were analysed using qualitative content analysis to facilitate examination of the explicit and observable content reported within the literature (Lindgren et al., 2020). Consistent with a manifest

content analysis approach (Kleinheksel et al., 2020), attention was directed towards identifying and describing recurring issues and concepts relevant to the study objectives rather than interpreting underlying meanings (see for instance, Andeobu et al., 2021b). All included studies were read repeatedly to ensure familiarity with the content, during which notes were used to identify recurring issues. Themes were developed iteratively through collaborative discussion among the authors, allowing recurring patterns across the literature to inform the analytical structure of the review.

Given the interconnected nature of e-waste management, findings from individual studies frequently informed multiple thematic categories where explicitly relevant to the study objectives. The resulting themes captured key dimensions of e-waste governance, including management practices, policy instruments, implementation barriers, and strategies towards sustainable management, thereby providing a structured synthesis of the literature. Although findings were organised into distinct themes, all included studies contributed to the overall synthesis and were cited where relevant to support the analysis (Fig. 2).

3. Results and discussion

This section presents a synthesis of the literature organised into four broad analytical categories: governance frameworks shaping e-waste management practices (sub-section 3.1), dominant management practices (sub-section 3.2), barriers to sustainable practices (sub-section 3.3), and key strategies for achieving sustainable e-waste management (sub-section 3.4). The categories were informed by the study objectives, while the interpretation of content within each category emerged through the iterative qualitative content analysis described in Section 2.3.

As many studies addressed multiple dimensions of e-waste governance, papers were not assigned exclusively to individual analytical categories. Instead, studies informed multiple themes where conceptually relevant. To minimise unnecessary repetition, articles were cited according to analytical relevance within subsections, despite often contributing to several related themes. Consequently, citation frequency does not necessarily reflect the extent of a study’s analytical contribution to the synthesis.

Table 2 summarises the key themes, their characteristics, and the frequency of contributing articles across thematic categories.

3.1. Governance frameworks shaping management

The WEEE Directive (grounded in EPR principle) and RoHS Directive (2002) constitute the principal regulatory instruments governing e-waste in the EU. They are widely discussed as mechanisms for standardising practices across member states (Jofre and Morioka, 2005; Goodship and Stevels, 2012; Salhofer et al., 2016). The RoHS Directive reduces environmental and health risks by restricting hazardous substances in EEE. It enhances recyclability and maintains fair competition among manufacturers and importers across the European market. The WEEE Directive on the other hand, mandates the separate collection and sustainable treatment of WEEE, establishing targets for collection, recovery and recycling. It strengthens efforts against illegal waste exports and reduces administrative burdens through the harmonization of national EEE registers and reporting formats (European Commission, 2025; Shittu et al., 2021).

The recast WEEE Directive (2012/19/EU) further strengthens EPR systems through stricter collection targets, weight-based performance indicators, and an expanded scope covering all EEE unless explicitly excluded (Niza et al., 2014; Habib et al., 2022; Fechner et al., 2012). These reforms have improved regulatory harmonisation and expanded coverage across member states, contributing to progress in countries such as Poland (Xu et al., 2025), and yielding progress in others (Johnson et al., 2018). Nevertheless, inconsistencies in interpretation and implementation persist across national contexts, causing some

⁴ The database search was conducted on June 29, 2025.

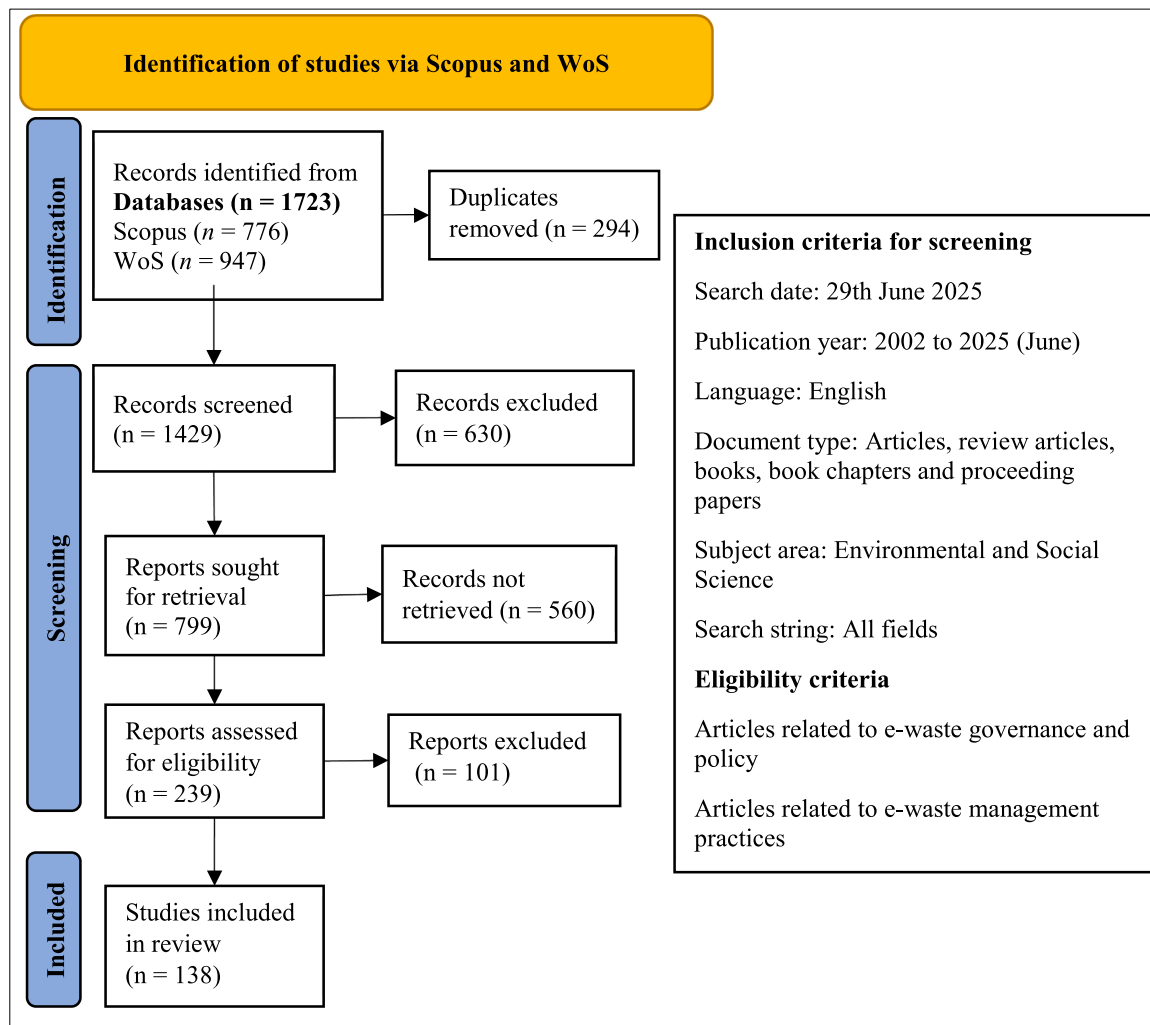


Fig. 1. PRISMA 2020 flowchart for systematic reviews (Adopted and modified from Page et al. (2021)).

countries, such as Italy, to struggle in meeting new targets (Constantinescu et al., 2022; Favot, 2014).

Similarly, the UK's Waste Electrical and Electronic Regulations (2006) operationalise EPR primarily through Producer Compliance Schemes (PCS), while Electronic Duty of Care (EDOC) systems support waste tracking and documentation, enabling registered entities to facilitate the collection, treatment, and recycling of WEEE (McNeill et al., 2021; Santos and Lopes, 2023). Thus, WEEE management in the EU27+UK is anchored in EPR, whereas the EU advances broader environmental objectives through international cooperation under the Basel Convention (Dreher and Pulver, 2008). However, reliance on weight-based metrics may misrepresent actual sustainability outcomes by prioritising heavier, low-value materials over critical hazardous components. Additionally, overly ambitious mass-based EPR targets risk increasing operational cost (Walther and Spengler, 2005).

Rapid technological change and emerging industries further challenge EPR implementation. Novel products often fall outside existing categories and contain complex or hard-to-recycle materials. For example, the rapid obsolescence of cryptocurrency mining hardware generates growing volumes of discarded electronic equipment that current EPR systems are insufficiently equipped to manage (de Vries and Stoll, 2021). These challenges contribute to the persistence of informal handling and illegal exports, which limit critical metal recovery and undermine the core intent of EPR systems (Wilts et al., 2011).

Although EPR frameworks have strengthened producer responsibility and improved recovery targets (Nicol and Thompson, 2007;

Goorhuis et al., 2012; Wang et al., 2017), their capacity to stimulate eco-design and product innovation remains limited (Gottberg et al., 2006). This is largely because EPR fees are insufficiently linked to product durability, recyclability, repairability, or other environmental performance criteria (Laubinger et al., 2021). Consequently, compliance obligations may constrain innovation, with firms focusing primarily on meeting WEEE requirements and managing imported products rather than investing in sustainable product design (Egüez, 2021; Giesecke and Tötzer, 2007). Economic considerations also continue to shape treatment decisions, potentially favouring technologically advanced options (Egüez, 2021).

Mayanti and Helo (2024) highlight that EPR implementation and waste reverse logistics vary across product categories, including EEE, with differences in the extent to which recycling, reuse, repair, and remanufacturing strategies are employed. In addition, the heterogeneous composition of e-waste complicates the development of management approaches tailored to specific materials and waste streams (Nain and Kumar, 2022). Although EPR places primary responsibility on producers, there is substantial disparities in collection and recycling rates. These inconsistencies reflect structural differences in national regulatory and institutional capacity, highlighting that the a one-size fits-all EPR policy is insufficient (Bucea-Manea-Țoniș and Zecheru, 2022; Santos and Lopes, 2023). As Mayers et al. (2005) note, the impacts of EPR are contingent on implementation processes that are in turn, shaped by national and cultural contexts (Bucea-Manea-Țoniș and Zecheru, 2022). To explore how contextual factors translate into

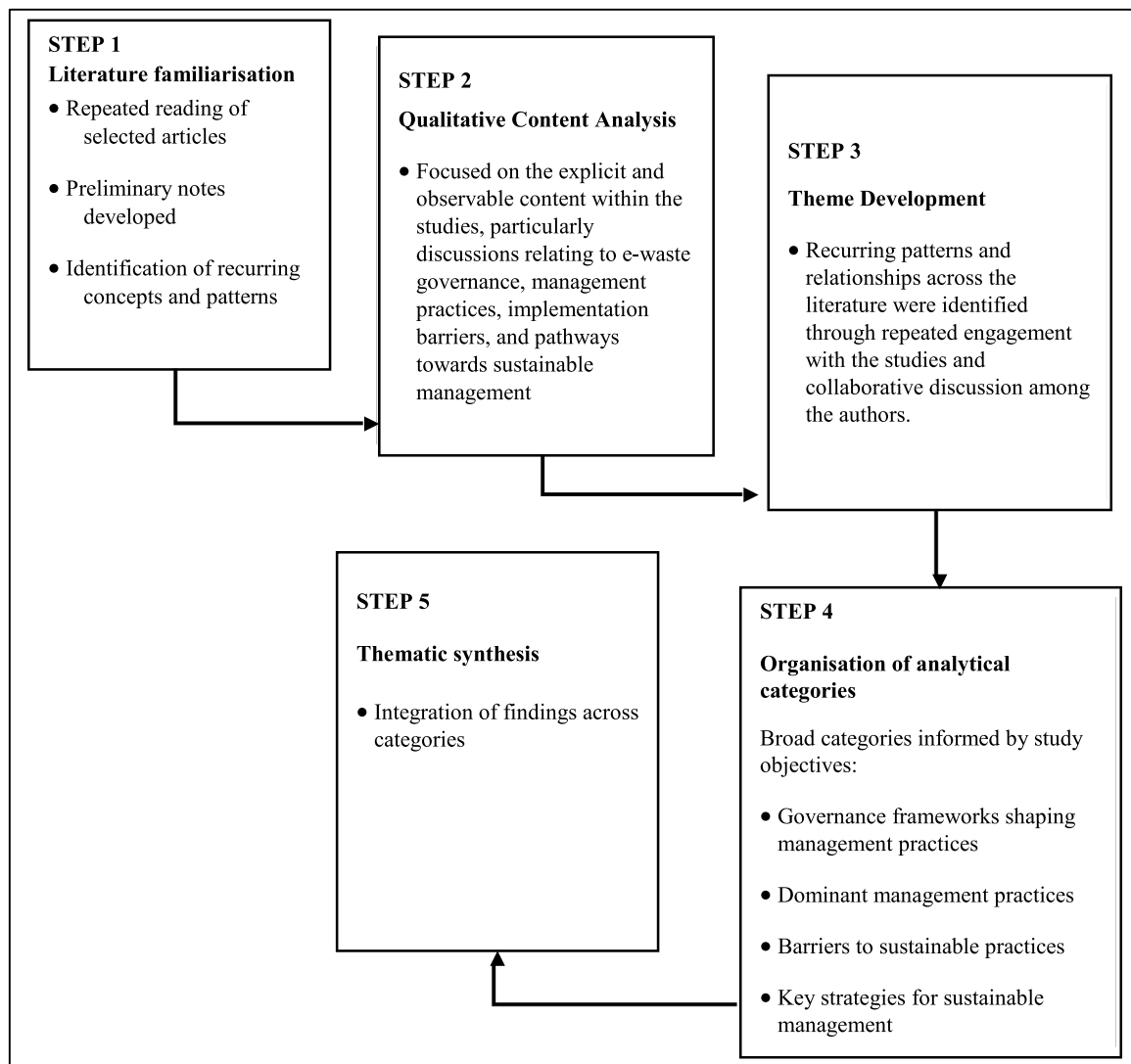


Fig. 2. A workflow detailing the thematic synthesis.

practice, the next section considers dominant e-waste management practices.

3.2. Dominant management practices

Waste management in the EU has been argued to contribute only marginally to climate change mitigation and environmental protection, as practices such as incineration, toxic emissions, and fuel-intensive recycling processes generate greenhouse gas (GHG) emissions (Sund et al., 2025). Nevertheless, effective collection and management of WEEE can yield significant GHG savings, underscoring the continued importance of e-waste management (Clarke et al., 2019; Jofre and Morioka, 2005). The growing emphasis on resource recovery, as noted by Shittu et al. (2021), has increasingly shaped e-waste management in the EU, with the review identifying re-use, servicing, remanufacturing, recycling and disposal as principal management practices— each discussed below.

3.2.1. Reuse and repair

Repair and component reuse are increasingly promoted as strategies for extending product lifespans and reducing material demand (Clarke et al., 2019; Jofre and Morioka, 2005; Mhatre et al., 2021). Purkiss et al. (2024) for instance, critique the UK's 'produce-consume-discard' model, arguing that a robust repair economy

could address environmental, social and economic challenges. Yet, Cole et al. (2019a, 2019b) highlight that repair and reuse practices are often neglected and restricted to specific products and small-scale operations, largely as a result of legislative design— indicating the need for structural reforms (Pencheva et al., 2025).

In response to such challenges, Zacho et al. (2018) propose a set of prerequisites for incorporating repair and reuse in Denmark's e-waste management system, including extended tendering periods, incentivised municipal waste authorities, engagement of qualified workers and quality assurance protocols, and measures to curb transboundary movement of EEE. While these measures can improve system effectiveness, they also require substantial institutional capacity and financial investment, potentially limiting their applicability in less developed or resource-constrained systems.

Importantly, assessments caution against assuming uniform benefits from repair and reuse. Kouloumpis et al. (2023) highlight that environmental impacts depend on device type and environmental indicators considered. Similarly, Boldoczki et al. (2021) demonstrate that even high reuse rates for washing machines in Germany yield limited environmental benefits, largely because of the operational energy and water use. Nonetheless, repair and reuse have environmental benefits as they keep products in use longer before they reach the end-of-life (EoL) stage (Clarke et al., 2019; Purkiss et al., 2024).

Table 2
Summary of analytical categories, themes and key characteristics.

Analytical categories	Themes	Key characteristics	Number of contributing articles
Governance frameworks	WEE Directive and Extended Producer Responsibility (EPR)	Provide regulatory frameworks governing producer accountability for e-waste management.	21
	RoHS Directive	Restricts the use of hazardous substances in EEE.	
Dominant management practices	Reuse and repair	Extending the lifespan of EEE through repair and reuse practices.	27
	Remanufacture and recycle	Recovering materials from e-waste for reintegration into production processes	
	Safe and responsible disposal	Household disposal behaviours play a critical role in waste recovery.	
Barriers to sustainable practices	Governance-related barriers	Policy deficiencies and regulatory gaps impede effective e-waste management.	45
	Operational and technical constraints	Inefficient collection systems contribute to reliance on informal disposal channels.	
	Behavioural challenges	Socio-cultural and demographic factors hinder the adoption of sustainable practices.	
Key strategies	Governance and regulation	Effective regulation, enforcement, and institutional coordination are essential for sustainable management.	84
	Technical and design innovations	Technological advancements and innovation can enhance sustainable management	
	Social dimension	Interventions addressing cultural and social factors can support sustainable practices.	
	Economic and financial recommendations	Eco-investment, modulated fees, and incentives can strengthen sustainable management.	

3.2.2. Remanufacture and recycle

Unlike repair and reuse, remanufacturing and recycling focus primarily on material recovery and product regeneration at EoL (Ghisellini et al., 2023; Jofre and Morioka, 2005; Mayanti and Helo, 2024; Mhatre et al., 2021; Wang et al., 2017). These practices play a pivotal role in enabling countries (e.g., Germany, France, Denmark, Greece and UK) to meet their WEEE targets and gain access to secondary raw material sources (Fechner et al., 2012; Peagam et al., 2013; Zacho et al., 2018; Aidonis et al., 2019), while also generating employment across the EU (Yang et al., 2021). Recycling also contributes to minerals and resource

conservation (Rachovides et al., 2024; Wang et al., 2017), with results from Belgium showing that desktop and laptop recycling can save resources (Van Eygen et al., 2016).

However, recycling systems remain biased toward bulk and easily recoverable materials (Cole et al., 2019a; Van Eygen et al., 2016). A typical example is the use of shredding technologies in recycling facilities, which prioritise the recovery of easily recyclable materials in large quantities (Cole et al., 2019b). This approach, along with other inefficiencies in recycling processes, is particularly problematic for small critical raw materials (CRMs) whose low concentrations and tiny size make them prone to being lost, potentially resulting in avoidable material losses (Campbell-Johnston et al., 2023; Vafeas et al., 2024). This underscores a misalignment between regulatory compliance and circularity, suggesting that current recycling processes may fail to capture full environmental and economic value (Vafeas et al., 2024). Consequently, such inefficiencies threaten the EU's green and digital transitions, which rely on secure and stable supplies of CRMs (Lattoni et al., 2025).

The human dimension of recycling and remanufacturing is also significant. Health and safety hazards persist even in advanced processes (Lecler et al., 2015), illustrating that recycling gains cannot be separated from occupational and environmental risks. Consequently, shifting beyond mass-based recovery metrics towards indicators that account for environmental, economic, and public health outcomes may provide a more balanced assessment of WEEE targets, particularly in light of changing market dynamics and EEE lifecycles (Habib et al., 2022). Bonoli et al. (2021) emphasise the importance of specialised recovery facilities and controlled industrial processes for improving rare earth element recovery from WEEE while limiting the release of hazardous substances.

3.2.3. Safe and responsible disposal

Nagase and Uehara (2024) indicate that increasing reuse and recycling alone has limited impact on reducing landfilled WEEE, whereas prolonged household use of EEE and improved collection systems are more effective, highlighting the pivotal role of households in the circular economy. At the household level, consumer attitudes, behaviours, and capabilities significantly influence e-waste management outcomes (D'Adamo et al., 2022). Yet, household-level practices and capabilities are not consistent across EU countries, indicating that behavioural interventions must be context-specific. Evidence from Ireland highlights the role of consumer knowledge and transport capacity as limiting factors (Ryan-Fogarty et al., 2021). Surveys in Lithuania also reveals that while awareness of WEEE's importance exists, significant knowledge gaps in sorting procedures and available disposal services inhibit proper management (Dagiliūtė et al., 2019).

Economic considerations further constrain participation. In Romania, reluctance to discard e-waste without compensation (Trentea et al., 2014) mirrors findings from Greece, where incentives are needed to increase collection (Achillas et al., 2010). This reinforces the pattern that without tangible or expected financial benefits, household participation in WEEE management could be limited. Davis et al. (2006) identify concern for future generations, reduced landfill dependence, and environmental and resource conservation as key motivations for participation in recycling. Thus, participation in WEEE management is influenced by both economic considerations and environmental concerns, highlighting the need for policies that combine financial incentives with sustainability awareness.

3.3. Barriers to sustainable practices

Despite the formal adoption of the WEEE Directive and related policy instruments, persistent governance, operational, technical, and behavioural barriers continue to hinder effective e-waste management across the EU (Magalini and Huisman, 2007; Narbón-Perpiñá and Prior, 2020). These challenges constrain the translation of policy objectives into effective practice (Mohanty et al., 2015). A detailed discussion of these

barriers follows.

3.3.1. Governance-related barriers

Limited capacity to implement the WEEE Directive, coupled with inconsistent policy integration, undermines effective e-waste management across the EU (Corsini et al., 2017; Aidonis et al., 2019; Campbell-Johnston et al., 2019). More specifically, fragmentation and inconsistencies across policy domains, insufficient CE criteria in procurement, difficulties in quantifying unregulated flows and limited CE standards are some identified obstacles (Rizos and Bryhn, 2022; Blasi et al., 2023; Habib et al., 2022). Broader socio-economic factors, including income inequality, corruption, population dynamics and, lack of local repair further undermine management practices (Neves and Marques, 2022; Nikou and Sardonou, 2023). These factors also contribute to the transboundary export of e-waste, shifting environmental burdens to developing economies and allowing exporting countries to bypass domestic responsibility (Bernard, 2015; Nikou and Sardonou, 2023).

The lack of multi-level stakeholder coordination (Pfeffer et al., 2025), poor enforcement and underfunded waste authorities (Herk and Bisschop, 2020) also inhibit management. Uneven enforcement creates fragmentation in management across countries (Yoshida and Yoshida, 2010), making some attain WEEE targets while others lag behind. Even context-specific legislations, such as Bulgaria's Strategy and Action Plan, are often underdeveloped, lack clearly defined indicators, and fail to implement planned monitoring systems (Goranova and Anguelov, 2024). Moreover, while EPR is often portrayed as a driver of eco-innovation, the literature reveals limited evidence of meaningful upstream transformation (Gottberg et al., 2006; Giesecke & Tötzer 2007).

3.3.2. Operational and technical constraints

Complexities in optimising WEEE collection, transportation and systems—driven by trade-offs between cost, operational efficiency and service quality (Cotta, 2020; Habib et al., 2022; Nowakowski et al., 2017), inadequate selective collection mechanisms (Marczuk et al., 2019), and time-sensitive barriers to value recovery (Richter et al., 2023) reduce official recovery rates, leaving room for informal and illegal practices. Such informal channels, alongside poor collection and trading of WEEE result in 'missing' flows that escape reporting and recovery (Curran and Williams, 2010; Sovacool et al., 2019; Cotta, 2020; Habib et al., 2022; Neves et al., 2024a). Unregistered, non-obligated flows—often involving free-riders such as unregistered retailers—further exacerbate discrepancies between the amount of waste generated and those officially collected (Reeve and Eduljee, 2019). Such irregularities undermine the effectiveness of formal take-back systems and complicate the fair allocation of producer responsibility, as evidenced in the German context (Rotter et al., 2011).

Moreover, reported recycling rates may be misleading, as weight-based metrics, while enabling consistent reporting (Habib et al., 2022), can overestimate or underestimate performance (Kama, 2015; Clarke et al., 2019), and undervalue certain materials with significant economic, environmental or resource potential (Ford et al., 2016). Furthermore, policy and practice often prioritise recycling activities (Trentea et al., 2014; Cole et al., 2019a, 2019b), which may undermine reuse and repair, and inadvertently stifle upstream interventions such as eco-design, thereby hindering waste prevention, material recovery and circularity (Staniskis and Stasiskiene, 2005; Parajuly et al., 2016; Roskladka et al., 2025; Nakajima and Vanderburg, 2005). Infrastructure deficiencies, diagnostic limitations, and inadequate technical expertise further restrict investment in sustainable product design and innovation (Corsini et al., 2017; Aidonis et al., 2019). This is particularly significant given evidence of a relationship between economic development and environmental sustainability objectives (Hume et al., 2002; Bernard, 2015; Constantinescu et al., 2022).

3.3.3. Behavioural challenges

Behaviour patterns complicate repair, reuse and disposal (Cole et al., 2019b). Evidence from the UK and Spain indicates that repair intentions are shaped by perceived control, attitudes, and cost, while reuse can mitigate inefficient overproduction and waste generation (González et al., 2017; Nadro et al., 2024). In other EU countries (e.g., Romania and Portugal), low public awareness of management strategies, limited understanding of its hazardous content and the benefits of WEEE management (Gutiérrez et al., 2010; Colesca et al., 2014; Delcea et al., 2020; Weilage et al., 2024), prevent household participation. Although greater awareness is necessary for effective management (as shown through the TRACE Project in the UK (Brock et al., 2022)), individuals' economic conditions also play a vital role in their willingness to participate (Achillas et al., 2010; Trentea et al., 2014).

Socio-demographic factors—including age, gender, and income—further affect participation. Even among receptive groups, these practices are not entrenched (Pérez-Belis et al., 2017; Neves and Marques, 2022). Cultural factors also play an important role—emotional attachment to devices in Ireland (Casey et al., 2019) and Greece (Menegaki and Kaliampakos, 2006) leads households to retain unused EEE rather than dispose them appropriately. These findings indicate that effective WEEE management requires not only regulatory and technical interventions, but also broader systemic and cultural shifts capable of supporting behavioural change and sustainable consumption practices (Cole et al., 2016; Pencheva et al., 2025).

3.4. Key strategies for sustainable management

The literature review identified four recurring and interrelated domains—governance, economic structuring, social dimension, and technical design—that consistently emerged across the reviewed literature as critical to addressing barriers to sustainable e-waste management. These domains were inductively derived through synthesis of strategies and interventions for effective management and form a conceptual foundation of the pathway proposed in this study. The following discuss each pillar and its significance for sustainable e-waste governance.

The governance and regulation pillar highlights the need for coherent regulatory structures, enforcement mechanisms, and institutional coordination in effective e-waste management (Parajuly et al., 2017; Egüez, 2021; Yang et al., 2021; Favot et al., 2022; Habib et al., 2022; Nikou and Sardonou, 2023; Mayanti and Helo, 2024; Vaduva et al., 2024; Börner and Hegger, 2018). Regulatory design can for instance, balance economic principles with technological developments (Wiesmeth and Häckl, 2011), differentiate fees based on EoL treatment costs (Mayers et al., 2013), allocate supply chain responsibilities (Corsini et al., 2017), harmonize WEEE and eco-design regulations (Svensson and Dalhammar, 2018; Vafeas et al., 2024), and improve material recovery quality across all e-waste categories (Chaine et al., 2023). In Scotland, reforms to EPR schemes are considered essential for improving resource efficiency and reducing dependence on virgin materials (Salemdeeb et al., 2022)—a concern echoed across the EU (Mayers, 2007). Favot and Marini (2013) emphasise the need for fair distribution of EPR-related expenses, as producers may otherwise shift economic burden to consumers.

Decentralised governance and local institutional capacity are also crucial, given the distinct challenges faced by different countries, and the multitude of actions to take at different scales (Sovacool et al., 2019). Successes in countries where local authorities actively shape management operations (Cahill et al., 2011), contrast with weaker results elsewhere, highlighting that local-level leadership and contextual adaptation can influence performance (Neves and Marques, 2022). Successful European models (e.g., the Netherlands' approach which emphasises on cooperation, high recovery rates and low costs (Raymond, 2002), and the UK's 'design, build, and operate' approach (Mayers and Butler, 2013)), underscore the importance of tailoring

systems. Rising WEEE generation highlights the need for improved regulatory and policy coherence and coordination across governance levels (Huisman and Stevels, 2005; Nguyen et al., 2024; Vaduva et al., 2024; Pakula et al., 2025). Bilitewski (2008), Linderhof et al. (2019) and Novais and Tavares (2025) highlight that effective governance—with context-specific approaches, clear roles, and strong coordination—is as important as the policies themselves. Yet, De Meester et al. (2019) emphasise that structural changes alone have limited impacts unless complemented by other factors.

Technical and design innovations pillar underline the significance of innovation in product design, recycling technologies, and CE models that reduce waste generation at its source and promote recovery (Thomas, 2003; O'Connell et al., 2013; Más and Kuiken, 2020). Technological innovations can facilitate hazardous substance removal (Kiritsis et al., 2003), and enhance preparedness for emerging waste streams (Malandrino et al., 2017; Bonoli et al., 2021). Innovations such as eco-modulation (Micheaux and Aggeri, 2021) and robust eco-efficiency data (Huisman and Stevels, 2005) offer potential breakthroughs. Yet, design-stage interventions are underexploited despite decades of policy development and recommendations (Warburg et al., 2005), a gap the EU Ecodesign for Sustainable Products Regulation seeks to address (European Union, 2024). While eco-design offers benefits, Svensson and Dalhammar (2018) and Fenwick et al. (2023) caution against viewing it as a guaranteed solution for recycling. They note that its effectiveness is context-dependent and that some measures intended to improve recyclability may have limited impact or even disrupt EoL recycling.

The **social dimension** pillar focuses on public awareness, behavioural patterns and concerns (Appolloni et al., 2021; Yang et al., 2021; Habib et al., 2022; Sasso, 2023), and citizen-led innovations and skills development (Bozkurt and Stowell, 2016; Delgado and Callén, 2017). Specifically, Salhofer et al. (2016) and Pérez-Belis et al. (2017) advocate for awareness campaigns, a strategy Clarke et al. (2019) argue should be a key focus of future policy development. However, social acceptability cannot operate in isolation from structural factors (e.g., accessible collection systems and regulatory frameworks), which are necessary to enable and sustain proper e-waste management. Waste sorting in Slovenia, for example, is shaped not only by individual choices but also by infrastructure, regulatory frameworks and operational standards (Olofsson, 2020). Thus, calls for awareness campaigns risk overstating individual responsibility while underestimating systemic barrier.

Economic and financial mechanisms pillar emphasise the importance of eco-investment, modulated fees, market incentives, and sustainable business practices that make e-waste management both viable and scalable (Constantinescu et al., 2022; Pfeffer et al., 2025; Yoshida and Yoshida, 2010). These mechanisms can ensure that Producer Responsibility Organisations (PROs) generate sufficient funds to cover full waste management costs and promote the development of greener products (Mayers et al., 2013; Favot et al., 2018), while simultaneously creating incentive mechanisms that reframe e-waste as a valuable resource (Parajuly and Wenzel, 2017). Strengthening economic mechanisms is therefore critical for addressing persistent gaps in eco-investment and improving the efficient implementation of EPR systems.

While these four core pillars provide a useful conceptual foundation, they are insufficient in isolation to guarantee sustainable management. Persistent tensions between economic growth imperatives and environmental objectives continue to undermine the strategic coherence of e-waste governance (Selin and VanDeveer, 2006). In practice, economic expansion remains the dominant policy priority across jurisdictions, and the ongoing circulation of WEEE through transboundary flows reflects the limits of national-level interventions, thereby highlighting the need for strengthened international coordination and more inclusive, multi-scalar stakeholder engagements (Yang et al., 2021; Habib et al., 2022; Mahmoudi et al., 2019). As Liu et al. (2023) note, e-waste is a global issue that requires international cooperation.

Furthermore, the strong correlation between e-waste generation and development indicators such as GDP and HDI (Namlis and Komilis, 2019) shows structural nature of the e-waste management challenge. In this context, management systems that fail to explicitly integrate justice concerns risk reproducing inequalities, particularly in developing economies where institutional capacity, labour conditions and environmental safeguards remain uneven (Bernard, 2015; Nikou and Sardanou, 2023; Zacho et al., 2018). Since outcomes are neither instantaneous nor fixed, and are influenced by evolving social, economic, and technological conditions, sustainable e-waste governance must be treated as a dynamic process rather than a fixed institutional design. Thus, continuous monitoring and periodic refinement of strategies are essential to ensure adaptive and effective interventions (Yano and Sakai, 2016; Johnson et al., 2018).

4. An integrated pathway for sustainable e-waste management

The SLR demonstrates that progress to sustainable e-waste management in the EU remains constrained by barriers despite decades of regulatory development (Magalini and Huisman, 2007; Narbón-Perpiñá and Prior, 2020). It also reveals a dominant focus on downstream practices—reuse, repair, recycling, and disposal—while upstream actions such as eco-design and sustainable production are comparatively neglected (Mahmoudi et al., 2019; Gaur et al., 2024). This imbalance reinforces a reactive rather than preventative orientation, limiting opportunities for long-term reductions in waste generation and circularity transitions.

Consequently, the findings suggest that sustainable e-waste management requires a coordinated approach that integrates governance and regulatory frameworks, economic and financial mechanisms, social considerations, and technical and design strategies (Murthy and Ramakrishna, 2022). This approach further enriches CE perspectives. While CE principles provide the sustainability logic—emphasising waste prevention, extending product lifecycles, and closing of material loops—existing CE-oriented framings (e.g., D'Adamo et al., 2022; Gaur et al., 2024) tend to privilege behavioural, regulatory or technological components.

Building on broader circular economy and sustainability scholarship, the proposed framework incorporates two principles— inclusive and multi-scalar governance, and adaptive systems integration (Ashton et al., 2022; Corvellec et al., 2022; Teixeira, 2025). The relationship between the four pillars and the two principles is complementary and mutually reinforcing. While the four pillars represent the substantive domains necessary for sustainable e-waste management, the principles of inclusive and multi-scalar governance and adaptive systems integration provide the cross-cutting conditions through which these domains are coordinated, implemented, and sustained.

Specifically, inclusive and multi-scalar governance strengthens alignment across actors, governance levels, and jurisdictions, ensuring that responsibilities, resources, and decision-making processes are effectively integrated across all pillars (Heacock et al., 2016; Arya and Kumar, 2020; Ogunseitan, 2023; Cao et al., 2024; Grandhi et al., 2024; Purkiss et al., 2024). Adaptive systems integration on the other hand, supports cohesion among the pillars by promoting systems thinking, continuous monitoring, and iterative learning in response to evolving social, economic, technological, and regulatory conditions (Bernard, 2015).

These principles reinforce the interdependence of the pillars—for example, governance structures influence the design and enforceability of economic instruments, financial mechanisms shape the feasibility of technological innovation, and social engagement affects system uptake and long-term legitimacy. Consequently, sustainable outcomes depend not only on the strength of individual pillars, but also on the principles that enable their coordination and continuous adaptation. Weakness in either the pillars or the cross-cutting principles may compromise overall system effectiveness, underscoring the need for

integrated and coordinated e-waste governance (Liu et al., 2023; Serpe et al., 2025). Together, these elements inform the synthesis presented in Fig. 3.

Operationally, a national e-waste system aligned with this framework would integrate regulatory oversight, economic incentives, social engagement, and technological innovation through coordinated multi-level governance arrangements. This could include harmonised EPR schemes with eco-modulated fees linked to product durability and recyclability (Laubinger et al., 2021); national digital tracking systems for monitoring collection, recovery, and transboundary flows (Götz et al., 2022); stakeholder platforms involving producers, recyclers, local authorities, consumers, and informal actors (Blomberg et al., 2023; Purkiss et al., 2024); and periodic policy reviews to enable adaptive responses to emerging technologies and changing waste streams (O'Riordan et al., 2022; Cramer, 2023).

Existing systems in Germany, Sweden, UK, Italy, and France operationalise elements of the proposed framework through advanced collection, recycling and Extended Producer Responsibility (EPR) mechanisms, illustrating how governance, financing, technological innovation, and social engagement collectively shape e-waste management outcomes (Ahlers et al., 2021; Constantinescu et al., 2022; Edwards, 2021). For instance, Germany's EPR system has strengthened collection performance and producer accountability, while Italy's experience highlights the role of public awareness and municipal coordination in improving recycling outcomes (Ahlers et al., 2021; Torretta et al., 2013). Consequently, the proposed pathway should be understood not as a replacement for existing frameworks, but as an integrative model for strengthening coordination and adaptive capacity within national e-waste governance systems. The contribution of this pathway is fourfold. First, it responds to gaps in CE scholarship, which has often prioritised regulatory or technological solutions, while neglecting socio-economic dynamics. It expands the CE conversation to include governance quality, stakeholder inclusion, and justice-oriented considerations. Second, it consolidates empirical findings from diverse strands of research on e-waste, addressing the fragmentation that has limited the development of coherent strategies. Third, it reframes e-waste

governance as a complex phenomenon requiring both structural and behavioural interventions, thereby challenging narrowly focused approaches. Finally, it provides a practical and theoretically framework to support policymakers and practitioners in designing sustainable e-waste management strategies, thus bridging the gap between theory and actionable policy.

5. Conclusion

The findings reveal that despite established policies such as WEEE and RoHS Directives, e-waste management remains largely centred on reuse, recycling, and responsible disposal, with comparatively limited emphasis on upstream interventions. Governance, operational, and behavioural barriers continue to constrain sustainable outcomes, underscoring the need for a more integrated approach capable of addressing these interconnected challenges. Accordingly, this study proposes a framework comprising four interdependent pillars—governance and regulatory frameworks, economic and financial mechanisms, social dimensions, and technical and design innovations—underpinned by inclusive multi-scalar governance and adaptive systems integration. Together, these elements reframe sustainable e-waste management as a complex challenge requiring coordinated, multi-level, and adaptive interventions (Murthy and Ramakrishna, 2022; Thapa et al., 2023).

Although this review focuses on the EU context, the findings may hold broader relevance for other developed economies characterised by comparable regulatory structures, technological infrastructures, and consumption patterns. This study is not without limitations. The search criteria may have excluded relevant information from broader academic sources, grey literature, policy reports, and industry documents. As the study synthesised reported findings rather than primary empirical data, the conclusions are inherently shaped by the scope, quality, and analytical frameworks of the existing literature.

Future research should address these limitations by incorporating broader sources of evidence, including practitioner knowledge, policy evaluations, and industry data, to capture emerging governance and

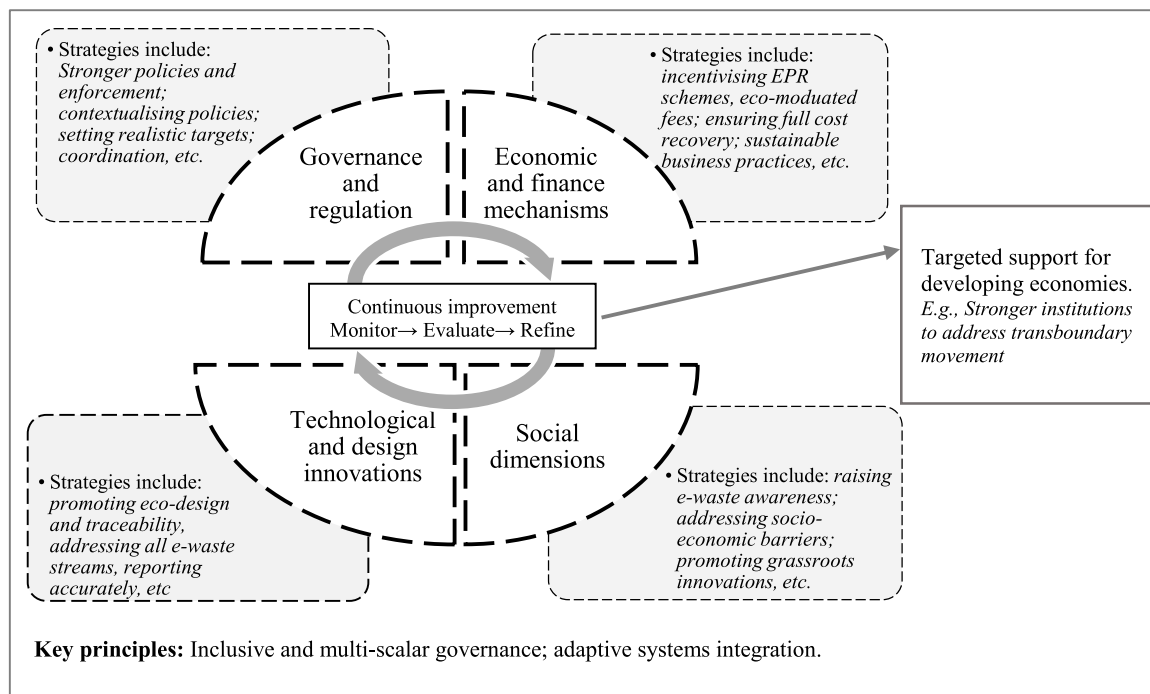


Fig. 3. An integrated pathway to sustainable e-waste management, incorporating four distinct but interconnected pillars. Note: Elements within the short dashes are drawn from the SLR.

Key principles: Inclusive and multi-scalar governance; adaptive systems integration.

technological developments. Empirical studies are needed to examine how the four-pillar approach operates in practice, particularly in low- and middle-income countries where international flows, informal-sector activity, and institutional constraints shape e-waste dynamics. Comparative and longitudinal research could assess how governance, economic incentives, social behaviours, and design innovations interact over time to support or hinder circularity.

CRedit authorship contribution statement

Dickson Boateng: Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Michael Breen:** Writing – review & editing, Supervision, Project administration, Funding acquisition. **Danny Marks:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Nicholas O'Neill:** Writing – review & editing, Conceptualization.

Declaration of competing interest

The corresponding author is currently engaged (2023–2027) as a paid consultant for ECORYS Nederland B.V., which is contracted by the European Union on matters unrelated to e-waste or the subject of this article. This consultancy had no role in the research, analysis, or writing of the manuscript.

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Data availability

No data was used for the research described in the article.

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