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Research Article

Hybrid Vision – Language & Knowledge-Graph Framework for Circular Construction Waste

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Abstract

Construction activities generate significant amounts of waste, posing serious challenges to environmental sustainability and resource efficiency. Circular economy strategies, particularly the 5R principles (Reduce, Reuse, Recycle, Recover, and Dispose), provide a structured approach for improving construction waste management; however, effective implementation on construction sites remains difficult due to visual complexity, mixed materials, and limited decision-support tools. Existing waste monitoring methods, including vision-based and data-driven approaches, often lack reliability, interpretability, and alignment with circular-economy-oriented decision-making. This paper proposes a hybrid conceptual framework that integrates Vision–Language Models (VLMs) with a knowledge-graph-based logical reasoning engine to support circular construction waste management. In the proposed approach, VLMs interpret construction-site images and extract semantic information related to waste materials and contextual conditions. The extracted information is structured within a knowledge graph, where a logical reasoning engine applies rule-based inference aligned with the 5R principles to ensure consistent, transparent, and explainable waste classification and handling decisions. By embedding circular economic logic as a dedicated decision layer, the framework shifts the role of AI systems from simple waste detection toward sustainability-driven decision support. The paper reviews related work on construction waste management, vision-based waste detection, and knowledge-driven reasoning systems. It identifies key challenges and opportunities associated with intelligent waste monitoring on construction sites. The proposed framework demonstrates how combining multimodal perception, structured knowledge representation, logical reasoning, and human-in-the-loop feedback can enhance reliability, transparency, and sustainability. This work lays the foundation for developing practical, interpretable, and circular economy-oriented construction waste management systems.

Keywords: Construction Waste Management; Circular Economy; Knowledge Graphs; Vision–Language Models; Logical Reasoning; Sustainable Construction.

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1 Introduction

The construction industry is one of the largest contributors to global waste generation, producing substantial material waste throughout project lifecycles (Sun, 2025). Construction waste increases project costs and causes significant environmental impacts, including resource depletion, landfill overuse, and greenhouse gas emissions (Cosoli, 2024). Improving construction waste management is therefore essential for achieving sustainability goals and reducing the environmental footprint of the built environment (Olawade, 2024 & Sivashanmugam, 2023).

In response, circular economic principles have gained increasing attention in construction research and practice. Rather than following linear “take–make–dispose” processes, circular economy strategies aim to minimize waste generation and maximize resource efficiency (Swarnakar & Khalfan, 2024). The 5R principles Reduce, Reuse, Recycle, Recover, and Dispose provide a structured framework for guiding waste-management decisions on construction sites (Jegen, Gast, & Faulstich, 2025). Effective implementation requires timely waste identification, assessment of material conditions, and informed handling decisions (Iuorio, 2025).

Despite growing awareness, current waste monitoring and management methods remain limited. Traditional approaches rely heavily on manual inspection and worker experience, making them time consuming, error-prone, and difficult to scale (Cosoli, 2024). Recent advances in computer vision and artificial intelligence have enabled automated waste detection from site images and videos (Alimi, 2025). However, most existing systems focus mainly on visual recognition, often struggling with mixed or contaminated materials, lacking contextual understanding, and providing limited support for circular-economy-oriented decision-making (Lopes, Cury, & Mendes, 2024).

Furthermore, many data-driven models operate as “black boxes” offering limited transparency and explainability, which reduces trust and usability in real construction environments (Malla, Bazli, & Arashpour, 2025). Vision–Language Models (VLMs) provide new opportunities by jointly interpreting visual and textual information to generate richer semantic descriptions of construction scenes (Ranjbar, Ventikos, & Arashpour, 2025).

Nevertheless, VLMs alone may produce uncertain or inconsistent outputs in complex environments, which is problematic for waste management tasks requiring consistency, accountability, and regulatory compliance (Adil, 2025). To enhance reliability and interpretability, this paper proposes a hybrid framework integrating Vision–Language Models with a knowledge-graph-based logical reasoning engine. Semantic information extracted by VLMs is structured within a knowledge graph representing relationships among waste materials, site conditions, regulations, and circular economy principles. A rule-based inference mechanism aligned with the 5R principles generates consistent and explainable waste classification and handling decisions.

By combining multimodal perception, structured knowledge representation, and logical reasoning, the framework moves beyond waste detection toward circular economy-oriented decision support. The objective of this paper is to explore how a hybrid Vision–Language and knowledge-graph reasoning framework can support circular construction waste management through reliable waste identification, structured reasoning, and transparent 5R-oriented decision-making.

The main contributions of this work are threefold:

1. Reviews research on construction waste management, vision-based detection, and knowledge-driven reasoning.
2. Highlights key challenges and research gaps in intelligent, sustainable waste monitoring.
3. Proposes a hybrid VLM–knowledge-graph framework combining multimodal perception, reasoning, and human feedback for circular economy implementation.

2 Related Works

Construction waste management has received increasing attention due to its significant environmental, economic, and social impacts (Ikponmwosa, 2024). Traditional waste management practices typically follow linear processes in which waste is generated, collected, transported, and disposed of, often resulting in inefficient resource utilization and high landfill dependency (Wu, 2025). To address these limitations, circular economic principles have been increasingly adopted in the construction sector. The 5R framework, Reduce, Reuse, Recycle, Recover, and Dispose, provides structured guidance for sustainable waste-handling strategies (Fereydooni Eftekhari, 2025). Previous studies have explored approaches such as selective demolition, material reuse planning, on-site sorting, and lifecycle optimization. However, implementing these strategies in real construction environments remains challenging due to heterogeneous, mixed, and contaminated waste streams (Cosoli, 2024; Olawade, 2024).

Recent advances in computer vision and artificial intelligence have enabled automated monitoring of construction-site activities. Deep learning and object detection approaches have been widely applied to identify construction waste materials from images and videos captured by cameras, drones, or mobile devices (Dodampegama, 2024 & Sun, 2025). While these approaches show promising performance under controlled conditions, their effectiveness often decreases in real-world scenarios due to occlusions, cluttered environments, lighting variations, and material contamination (Ranjbar, 2025). Furthermore, most vision-based approaches focus mainly on waste recognition rather than decision support aligned with circular economic principles (Iuorio, 2025).

In parallel, knowledge graphs and ontology-based approaches have been applied in construction research for structured knowledge representation, lifecycle analysis, and regulatory compliance modelling (Weerakoon, 2025 & Wu, 2025). BIM-integrated approaches have also been explored for structured waste quantification and circular economy assessment across building lifecycles (Iuorio, 2025), further demonstrating the value of information-rich models for sustainability-oriented decision support.

Despite this progress, these methods improve interpretability through rule-based reasoning but typically rely on restructured data and are not directly connected to real-time visual perception from construction site imagery (Wu, 2025). Vision–Language Models (VLMs) have recently emerged as a powerful multimodal approach capable of generating richer semantic descriptions of construction scenes. However, VLMs rely mainly on probabilistic inference, which may produce uncertain or inconsistent outputs in visually complex environments (Malla, 2025 & Sivashanmugam, 2023).

A comparative summary of existing research directions, their primary focus, and key limitations is presented in Table 1. Recent research in neuro-symbolic artificial intelligence suggests that integrating neural perception models with structured reasoning mechanisms, such as knowledge graphs and rule-based inference, can improve decision transparency and consistency.

Table 1: Comparative Overview of Existing Approaches and Research Gaps.

Research Area	Representative Studies	Focus	Identified Gaps
Traditional construction waste management	(Swarnakar & Khalfan, 2024. Fereydooni Eftekhari ,2025)	Waste quantification and disposal workflows	Linear processes; limited sustainability integration
Circular economy in construction	(luorio,2025; Swarnakar &Khalfan, 2024; Jegen, Gast & Faulstich, 2025)	5R strategies, reuse and recycling	Difficult implementation on dynamic sites
Vision-based waste detection	(Adil, 2025; Olawade ,2024. Swarnakar & Khalfan, 2024. Ranjbar, Ventikos & Arashpour, 2025)	Image-based waste classification	Limited reasoning and explainability
Knowledge graph /Ontology approaches	(Malla, Bazli & Arashpour, 2025; Ranjbar, Ven-tikos & Arash-pour, 2025. Wu, 2025)	Structured reasoning and rule-based decisions	Lack of real-time perception integration
Vision–Language Models (VLMs)	(Swarnakar & Khalfan, 2024. Jegen, Gast & Faulstich, 2025. Ranjbar, Ventikos & Arashpour, 2025)	Multimodal semantic scene understanding	Probabilistic and inconsistent outputs
Neuro-symbolic AI approaches	(Alimi, 2025. Singh, Azad &Mishra, 2024. Swarnakar & Khalfan, 2024)	Integration of perception and reasoning	Limited application to construction waste

As shown in Table 1, existing studies focus mainly on either vision-based perception or structured reasoning, while integrated frameworks combining multimodal Vision–Language perception with knowledge-graph-based reasoning for circular construction waste management remain limited. This gap motivates the proposed hybrid framework, designed to provide reliable, explainable, and sustainability-oriented decision support aligned with the 5R principles.

3 Challenges and Opportunities in Intelligent Construction Waste Management

Intelligent construction waste management systems face several challenges due to the complex visual, material, and operational characteristics of construction environments (Swarnakar & Khalfan, 2024). A major issue is the visual ambiguity of waste materials, which often appear irregular, fragmented, or degraded. Materials such as wood, concrete, insulation, and plaster may exhibit similar textures and colours when broken or mixed with debris, reducing the reliability of automated visual classification (Dodampegama, 2024).

Another challenge is the frequent presence of mixed and contaminated waste streams. On active construction sites, waste is rarely separated at the source, resulting in combinations of recyclable, reusable, and non-recyclable materials (luorio, 2025). Contamination from moisture, adhesives, coatings, or chemical residues further complicates material assessment and limits circular economy strategies (Jegen, Gast & Faulstich, 2025). Accurately identifying material condition and reuse potential remains difficult for systems to rely solely on visual data. Reliability and interpretability are also key concerns in AI-driven waste management. Many approaches are purely data-driven and lack explicit reasoning mechanisms, leading to inconsistent or uncertain outputs in complex conditions (Ranjbar, Ventikos & Arashpour, 2025; Wu, 2025).

In sustainability-focused applications, unexplained or contradictory recommendations reduce trust and hinder adoption. Practical deployment adds complexity, as construction sites are dynamic environments with changing layouts, lighting, weather exposure, and occlusions that can degrade model performance (Swarnakar & Khalfan, 2024; Sun, 2025). Computational, scalability, privacy, and integration challenges call for intelligent waste management frameworks combining robust perception

with transparent reasoning. As shown in Figure 1, key challenges in intelligent construction waste management, such as data uncertainty, mixed waste streams, limited transparency, and practical deployment constraints, negatively influence the effectiveness of the 5R principles, reducing efficiency in reducing, reusing, recycling, and recovering materials while increasing reliance on disposal.

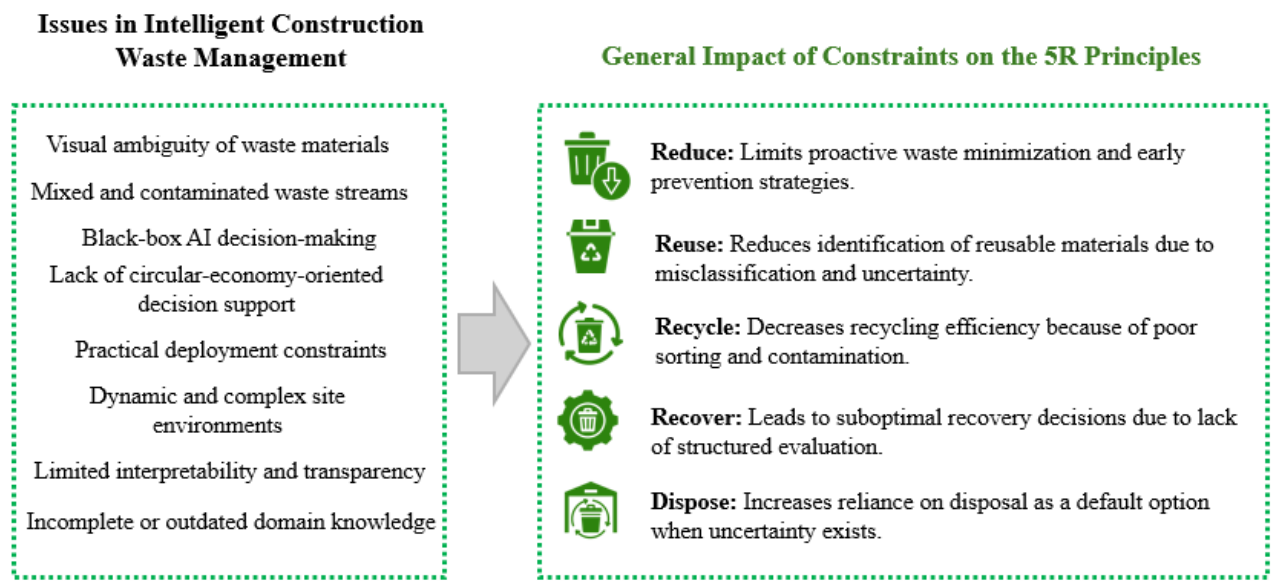


Figure 1: Key Factors and Their Impact on the 5R Principles

Integrating Vision–Language Models (VLMs) with knowledge-graph reasoning can address these challenges by combining visual perception and language understanding to generate semantic descriptions of waste materials and capture contextual relationships on construction sites (Ranjbar, 2025; Swarnakar & Khalfan, 2024). Perception alone cannot ensure reliable, circular-economy-aligned decisions. A knowledge graph adds structured reasoning that improves consistency and interpretability by modeling relationships among materials, contamination, regulations, and 5R rule (Dodampegama, 2024; Jegen, 2025). Rule-based inference then supports appropriate waste-handling strategies and ensures logical alignment between observed materials and circular economic actions.

This reasoning layer reduces contradictory outputs from probabilistic perception models, especially with mixed or contaminated waste, by encoding domain knowledge to ensure traceable, sustainability-aligned decisions (Wu, 2025). Separating perception (VLM) from reasoning (knowledge-graph inference) also improves explainability and practitioner trust by providing transparent decision pathways that link observed waste characteristics to recommended actions (Dodampegama, 2024; Lopes, 2024). Such transparency supports validation by site managers and compliance with regulations.

Furthermore, the hybrid framework aligns naturally with the 5R principles of the circular economy. The reasoning layer prioritizes reduction, reuse, and recycling before recovery or disposal, embedding sustainability directly into decision-making.

As a result, the system shifts from passive waste detection to active, circular-economy-oriented decision support. Overall, integrating multimodal perception with knowledge-graph-based reasoning enhances reliability, transparency, and sustainability alignment in intelligent construction waste management. The following section presents the proposed hybrid framework designed to operationalize these opportunities in practical construction environments.

4 Proposed Hybrid VLM–Knowledge-Graph Framework for Circular Construction Waste Management

The proposed framework introduces a hybrid neuro-symbolic architecture that integrates Vision–Language Models (VLMs) with a knowledge-graph-based logical reasoning system to support circular construction waste management. The main objective of this framework is to combine multimodal perception, structured knowledge representation, and explainable reasoning to enable reliable and sustainability-oriented decision-making on construction sites. By linking data-driven visual understanding with rule-based inference, the framework addresses limitations of purely vision-based or purely symbolic approaches and provides transparent decision support aligned with circular economy principles.

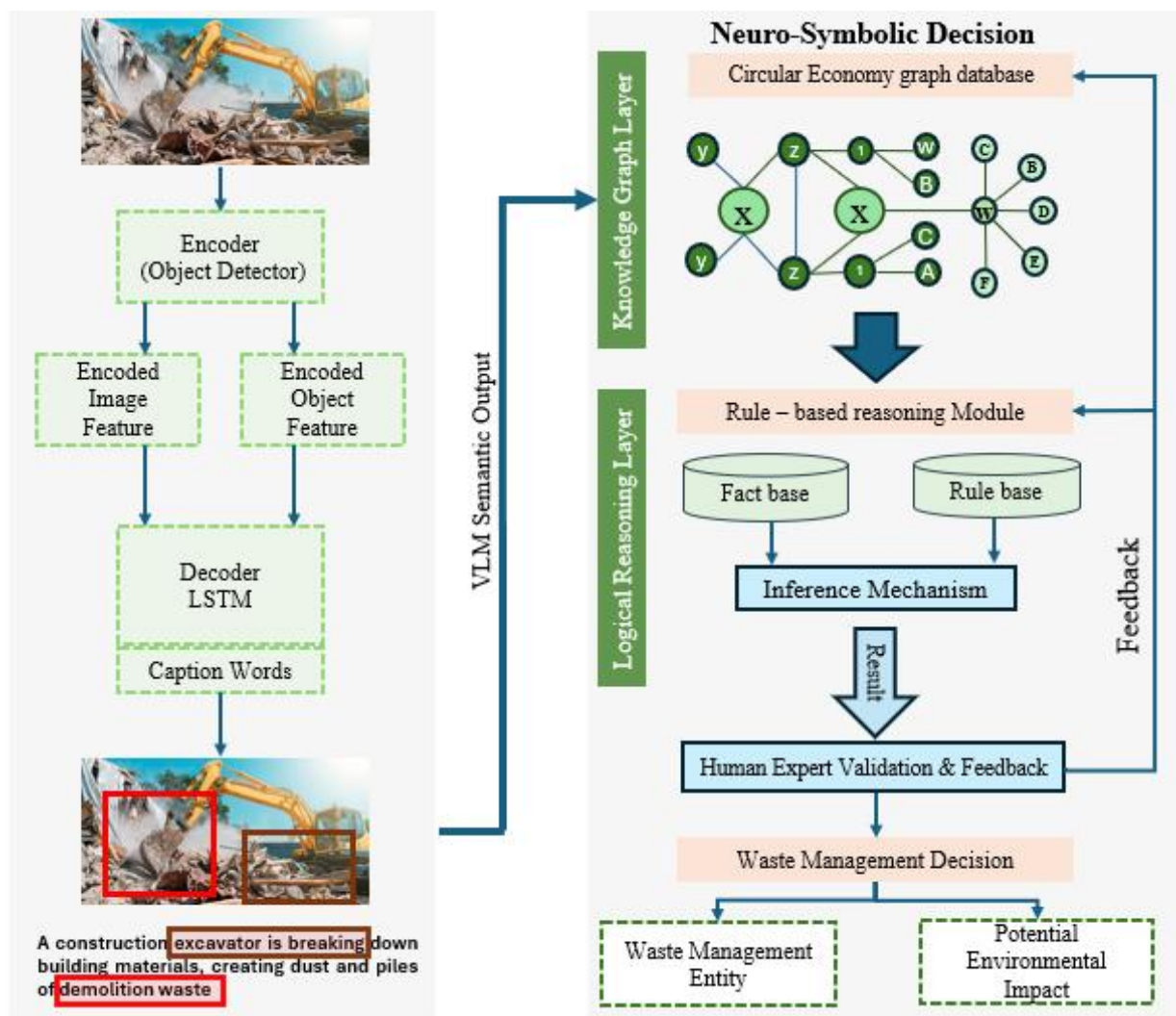


Figure 2: Hybrid VLM–Knowledge Graph Framework for Construction Waste Management

As shown in Figure 2, the framework begins with a Vision–Language perception component responsible for interpreting construction-site images. Visual data collected from cameras or mobile devices is processed through an encoder that detects objects and extracts features related to construction materials and waste elements. A decoding process generates semantic descriptions capturing material categories together with contextual information such as material condition, fragmentation, and surrounding site activities. Unlike conventional object detection methods that output only class labels,

the VLM combines visual and linguistic understanding to produce richer semantic descriptions, enabling better representation of complex and mixed waste scenarios.

The semantic output generated by the VLM is then structured within a knowledge graph that organizes relationships among waste materials, site conditions, circular economic concepts, and regulatory constraints. Entities represent materials, environmental factors, and management actions, while edges define logical relationships such as compatibility, contamination dependency, reuse potential, and recycling feasibility. The knowledge graph serves as a structured decision layer that integrates domain knowledge with perception results, ensuring that reasoning relies on explicit, interpretable relationships. This structure also supports scalability and future updates as new materials, rules, and environmental considerations are introduced.

Building on this representation, a logical reasoning engine applies rule-based inference to generate consistent, explainable waste-management decisions aligned with the 5R principles of the circular economy: Reduce, Reuse, Recycle, Recover, and Dispose. The inference mechanism evaluates observed material properties against predefined rules to determine suitable handling strategies. For instance, reusable and uncontaminated materials may be prioritized for reuse, while mixed or degraded materials are directed toward recycling or recovery. This reasoning layer reduces uncertainty from probabilistic perception models and provides transparent decision pathways that can be validated by practitioners.

To enhance reliability and practical applicability, the framework incorporates a human-in-the-loop validation stage in which construction managers or domain experts review recommendations and provide feedback. In practice, this feedback loop operates at two levels. At the instance level, a site manager reviewing a specific output can accept, reject, or correct the suggested handling action through a simple interface. Rejected or corrected outputs are logged as labelled examples that trigger targeted updates to the corresponding knowledge-graph rules, for instance, revising a contamination threshold or reclassifying a material-condition relationship.

At the systemic level, accumulated corrections are periodically analyzed to identify recurring misclassifications, which may indicate either gaps in domain knowledge or changes in site-specific conditions. These insights inform structured knowledge-graph updates, such as the addition of new material entities, revised edge weights, or updated regulatory constraints, allowing the graph to evolve with operational experience. This iterative refinement mechanism ensures that the framework remains aligned with practical requirements and improves progressively over deployment cycles.

The outcome of the framework is an explainable waste management decision that links visual observations to sustainability-oriented actions. Rather than focusing only on waste detection, the approach provides actionable recommendations aligned with circular economy strategies, shifting AI-assisted construction waste management from passive monitoring toward active and transparent decision support. To illustrate how the framework operates end-to-end, consider a concrete scenario: a site camera captures an image of a mixed pile containing broken ceramic tiles, timber offcuts, and partially contaminated plasterboard fragments during a building refurbishment. In the perception stage, the VLM processes the image and generates semantic descriptions for each identified material, including estimated condition (broken but structurally intact for tiles; clean and reusable for timber; moisture-contaminated for plasterboard) and contextual notes such as proximity to a drainage channel. These descriptions are translated into structured entities and relationships within the knowledge graph. In the reasoning stage, the inference engine evaluates the tile entities against reuse and recycling rules:

the tiles are classified as suitable for recycling given their intact condition and absence of chemical contamination, and a Recycle recommendation is issued with a traceable justification. The timber offcuts satisfy the reuse condition (no contamination, structural integrity retained), and a Reuse action is recommended. The plasterboard, flagged with moisture contamination, fails the recycling threshold rule and is directed toward appropriate disposal, with the contamination relationship made visible in the decision log. The output presented to the site manager identifies three material streams, their recommended actions, and the specific rules that generated each recommendation. If the manager disagrees for instance, knowing that the timber has surface paint containing lead this correction is logged, the timber entity is updated with a chemical-contamination flag, and the handling action is revised to recovery or disposal. This single interaction enriches the knowledge graph for future similar cases, demonstrating the practical value of the human-in-the-loop mechanism.

5 Discussion

The proposed hybrid Vision–Language and knowledge-graph-based reasoning framework has significant implications for advancing sustainable construction practices. By integrating multimodal perception with structured inference aligned with the 5R principles, it moves beyond conventional waste detection toward explainable, circular-economy oriented decision support. The system can assist site managers in improving sorting accuracy, reducing material loss, prioritizing reuse and recycling, and minimizing landfill dependency.

The integration of Vision–Language Models (VLMs) enables richer semantic understanding of construction-site conditions, while the knowledge-graph reasoning engine ensures consistent, transparent, and rule-based decisions. Separating perception from reasoning enhances interpretability and traceability, addressing limitations of purely data-driven AI systems. Embedding circular economy principles within the reasoning layer supports more systematic and accountable sustainability practices.

Despite its contributions, the framework has limitations. It remains conceptual and lacks empirical validation under real-world construction conditions, where site variability may affect performance. Its effectiveness also depends on the quality and completeness of encoded domain knowledge and decision rules; incomplete rules or outdated regulations may reduce reliability. Developing and maintaining a comprehensive, adaptable knowledge graph across diverse contexts is therefore challenging.

In addition, practical deployment requires addressing data availability, computational constraints, privacy concerns, and workflow integration through user-friendly interfaces and efficient data pipelines aligned with industry standards. Future research should focus on prototype development, multimodal dataset collection, and empirical evaluation of classification accuracy, reasoning consistency, transparency, and user acceptance. Comparative studies with purely vision-based systems would clarify the added value of structured knowledge-graph reasoning. User-centered evaluations involving site managers and sustainability professionals are also essential.

Further work may explore adaptive knowledge-graph updates, integration with Building Information Modeling (BIM), and scalable deployment across multi-site projects. Overall, the proposed framework provides a foundation for integrating multimodal AI perception with structured sustainability reasoning in construction waste management. By combining semantic scene understanding with explicit circular

economic logic, it offers a promising direction for developing reliable, transparent, and scalable intelligent waste management systems that support more sustainable construction practices.

6 Conclusions

This paper examined hybrid AI techniques for circular construction waste management. By reviewing existing research and challenges in intelligent waste monitoring, it identified limitations of current vision-based and data-driven approaches, which often focus on detection accuracy while neglecting structured reasoning, interpretability, and alignment with circular economy principles. To address these gaps, it proposed a conceptual framework integrating Vision–Language Models (VLMs) with a knowledge-graph-based reasoning engine to enable reliable, explainable, and circular-economy-aligned decision-making. In this framework, VLMs provide multimodal semantic understanding, while the knowledge graph structures domain knowledge and supports rule-based inference aligned with the 5R principles: Reduce, Reuse, Recycle, Recover, and Dispose. The approach shifts AI from passive recognition to transparent, structured decision support, improving consistency, traceability, and accountability in waste classification and handling. Although conceptual, the framework provides a foundation for future research combining multimodal AI, knowledge-driven reasoning, and circular construction practices. Future work should focus on empirical validation, prototype development, and real-world deployment to assess performance, scalability, and user acceptance, advancing sustainable waste management through integration of perception, reasoning, and human expertise.

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No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest

The authors declare no conflict of interest.

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