

Environmental Impacts and Governance Pathways for Solid Waste Across the Building Life Cycle

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Abstract. As the challenges of global climate change grow increasingly severe, China's carbon-peak and carbon-neutrality targets are becoming a powerful driving force for green economic and social transformation. The construction industry, as a pillar of the national economy, accounts for 50.9% of the country's total carbon emissions across its life cycle, making it a key sector for energy conservation and emission reduction. This paper focuses on solid waste at four stages: planning and design, construction, operation and maintenance, and demolition and disposal. Construction produces 60%–70% of life-cycle solid waste. Renovation waste achieves a recycling rate lower than 10%, whereas demolition waste features complex mixed components and high output volumes. Landfilling it without sorting can seriously contaminate soil and groundwater. A life-cycle approach that integrates source reduction, process control, and end-of-life recovery can reduce building-related emissions. Drawing on zero-waste construction sites in Shenzhen, this paper proposes governance measures from institutional and social-participation perspectives.

Keywords: Building solid waste, Life-cycle management, Resource recovery

1. Introduction

China aims to peak carbon emissions before 2030 and to achieve carbon neutrality before 2060. Low-carbon development is thus shaping industrial restructuring. The building industry is a national economic pillar, but it also consumes large amounts of energy and produces substantial emissions. According to the 2022 China Building Energy Consumption and Carbon Emissions Research Report, emissions from the construction process totaled 2.27 billion carbon dioxide (tCO₂) in 2020. That figure represented 50.9% of national carbon emissions and 45.5% of national energy consumption. Construction waste governance is therefore an urgent part of implementing the carbon targets [1].

Environmental pressures arise throughout the life cycle of a building. Open storage and landfill disposal of construction waste can pollute soil and groundwater. Hazardous wastes from construction or demolition may also enter municipal solid waste. And toxic components can spread during later transport and disposal. In addition, dust and fly ash from transport or poor disposal practices can pollute the air. This paper evaluates the environmental consequences of solid waste from building planning, design, construction, operation, and demolition under China's carbon agenda. It proposes green and recycled materials during design, local recovery of construction waste

during building work, and higher-value reuse during demolition. Finally, this paper draws on the experience of zero-waste construction sites in Shenzhen to propose a life-cycle strategy for the sustainable development of the industry.

2. Building life cycles and solid waste

2.1. Definition of the building life cycle

The building life cycle refers to the entire process from the early stage of strategic and needs definition, planning and project initiation, design and construction, to the mid-stage of completion, acceptance and usage, operation monitoring and renovation, and finally to the later stage of handover, demolition, disposal, and recycling of building materials. Figure 1 presents the sequence.

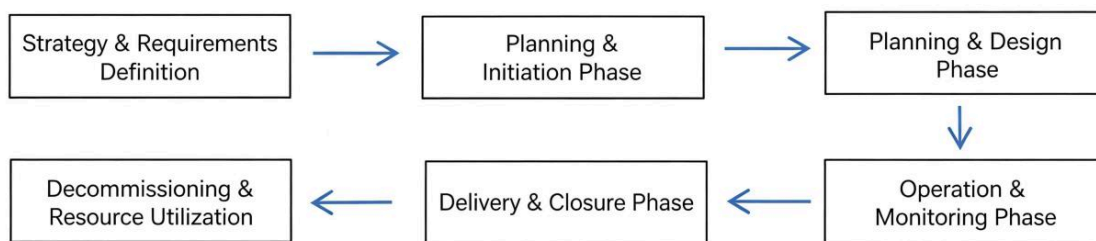


Figure 1. Schematic of the building life cycle

2.2. Definition of solid waste

Solid waste refers to all types of waste generated during the planning, design, construction, operation, maintenance, and demolition of buildings. Solid waste primarily includes construction waste, demolition debris, municipal solid waste, and waste building materials. Construction waste comprises excavated soil, broken bricks, sand, gravel, and slurry, which are mainly generated during construction. Demolition debris includes concrete fragments, bricks, tiles, and waste mortar generated from the demolition of old buildings and urban renewal projects. Municipal solid waste consists of daily waste generated in construction site living quarters and office areas. Waste building materials include discarded doors and windows, waste pipes, waste insulation boards, and waste tiles.

2.3. The role of solid-waste governance in the construction industry's low-carbon transition

The volume of industrial solid waste (ISW) in the global industrial chain is growing exponentially, and traditional waste disposal methods—particularly landfilling—are becoming increasingly unable to meet industry demands [2]. Solid waste is produced in large quantities and is difficult to treat. Its generation, transport, and disposal are closely linked to carbon emissions. Cement, natural sand, gravel, and other building materials are major emission sources in construction. Recycled aggregate, fly ash, steel slag, and other solid wastes can replace virgin inputs. This substitution reduces emissions from limestone calcination and mining and lowers the embodied carbon of building materials. Systematic waste reduction, recovery, and harmless treatment are therefore important for low-carbon, high-quality development in construction.

3. Solid waste across the building life cycle

3.1. Planning and design

The planning and design phase has the most significant environmental impact throughout a building's entire life cycle. Although this phase itself generates very little solid waste, the initial design decisions determine the costs, the amount of solid waste generated, and the potential for resource recovery in all subsequent phases of the building's life cycle.

Green building materials made from solid waste can save energy, reduce carbon emissions, and be recycled while meeting basic safety and durability requirements. Selecting them during planning and design can protect human health and minimize life-cycle environmental impacts. For example, a material based on carbonized corn-straw core (CCSC) provides thermal insulation, sound reduction, and electromagnetic-interference shielding. It is a lightweight, high-performance, multifunctional material. It can also protect work spaces and electronic equipment from electromagnetic radiation, temperature variation, and noise, with potential applications in construction, transport, and space exploration [3].

As climate change has become more pressing, especially after China announced its carbon targets, life-cycle assessment has become a key analytical tool. Carbon emissions from green building materials are an important indicator. One study used indicator classification and expert interviews to develop an evaluation system with three primary indicators and twelve secondary indicators, as shown in Table 1 [4].

Table 1. Evaluation indicator system for green building material suppliers

Primary indicator	Secondary indicator
Product attributes	C1 Green building-material certification level
Product attributes	C2 Price and cost competitiveness
Product attributes	C3 Product quality stability
Product attributes	C4 Product carbon footprint
Performance capability	C5 Financial condition and reputation
Performance capability	C6 Production capacity and supply reliability
Performance capability	C7 After-sales service system
Green management	C8 Green management-system certification
Green management	C9 Resource and energy consumption
Green management	C10 Green logistics and packaging
Green management	C11 Recycling and waste management
Green management	C12 Green technology and innovation

3.2. Construction

Construction generates more solid waste than any other stage across a building's full lifespan, making up 60% to 70% of all life cycle waste output. On-site waste streams primarily consist of scrap metal, discarded timber, waste plastic, crushed glass and textile scraps, among which metal and wood residues dominate. Sorting waste into recyclable and non-recyclable fractions via standardized site management can raise resource recovery efficiency and cut overall waste disposal expenses.

On-site recycling is defined as the processing of construction debris directly within or adjacent to project sites, which eliminates the need for long-distance waste haulage. Industry practitioners now widely adopt three mature technical routes: mobile crushing and screening equipment, flow-state solidified soil technology, and recycled concrete preparation. Looking ahead, upgrading recycled materials for high-performance concrete will rely heavily on intelligent modification methods. By integrating material genome engineering with artificial intelligence, researchers can realize automated, precise adjustment of recycled aggregate performance for broader engineering applications [5].

3.3. Operation and maintenance

Solid waste generation slows during the operation and maintenance phase relative to construction, yet the lengthy service cycle of buildings leads to substantial cumulative waste volumes. Waste arising in this stage mainly comes from regular maintenance works, daily on-site municipal refuse, and renovation debris, with interior renovation waste standing out as the dominant stream.

Such renovation waste carries distinct management hurdles: it is produced sporadically across scattered locations, contains complex mixed impurities, and lacks predictable generation timelines. These traits complicate routine collection, transportation and subsequent resource recovery workflows. Most Chinese cities still adopt mixed collection for renovation waste streams. The vast majority of these materials ultimately end up in landfills, with their overall recycling rate falling below 10%. This practice not only wastes recyclable construction materials but also creates mounting pressure on urban landfill capacity.

Waste generated from interior decoration and renovation remains one of the most difficult fractions to recycle due to its diverse sources and highly composite composition. Two local waste recycling facilities have introduced artificial intelligence (AI) sorting equipment manufactured by Finnish firm Zen Robotics to address this challenge. After automated sorting, separable materials including metal, glass and timber are transported to dedicated reprocessing plants. Meanwhile, concrete, brick, stone and tile fragments are crushed on-site to produce recycled aggregates, which are further processed into recycled bricks, recycled aggregate concrete and recycled mortar for secondary construction use [6].

3.4. Demolition and disposal

Demolition and disposal conclude a building's life cycle and provide the principal source of materials for recovery. Demolition waste mainly includes waste concrete, bricks and tiles, scrap steel, and mixed light materials. It is produced in highly concentrated volumes and has an extremely heterogeneous composition. If it is landfilled without sorting, it consumes valuable land. Heavy metals and organic pollutants may also leach into the ground with rainwater and cause lasting soil and groundwater contamination.

Effective sorting helps shift construction solid waste away from low-value landfill treatment toward high-value material recycling. Separating different waste fractions and stripping impurities greatly raises the quality of recycled aggregates and finished building materials. Conventional sorting techniques such as manual picking, gravity separation, magnetic screening and wind classification suffer from low throughput and poor recognition precision, which cannot satisfy the standards required for high-value recycled products.

Recent progress in sensing and artificial intelligence has supported the deployment of robust intelligent sorting systems, covering visual identification, hyperspectral scanning and X-ray

detection.

4. Case study: zero-waste construction sites in Shenzhen

Futian District in Shenzhen has developed experience in advancing the Zero-Waste City initiative. Yuyuan Recycling Park provides a typical case.

Shenzhen's Municipal Bureau of Housing and Construction, together with other departments, issued a three-year construction-waste action plan containing 25 measures. The city also issued the Technical Standard for Construction Waste Reduction (SJG21-2025), a local standard that improves waste-generation estimates and reduction assessments. Futian has applied these measures actively. More than 95% of demolition waste in the district is recovered. Yuyuan Recycling Park uses recycled construction materials made from 565 tonnes of building waste and 12 tonnes of recovered tree waste. Building Information Modeling (BIM) simulates construction before work begins. Cameras and AI algorithms then identify waste materials at the site. These tools support an initial intelligent system that covers the full construction-waste process.

The combination of policy implementation and project practice has made zero-waste construction common in new Futian projects. Most new developments in the district recover construction waste efficiently. The approach provides operational experience for regular, larger-scale Zero-Waste City development.

5. Challenges and policy options for managing construction solid waste over the life cycle

5.1. Key challenges

The three main challenges are missing supporting incentives, weak treatment of renovation waste, and the high cost of higher-value technologies.

Current policy arrangements provide insufficient economic incentives for construction-waste reduction and recovery. They also lack a life-cycle system for tracking and assessing waste-generation data. Without supporting incentives, solid-waste governance is difficult to advance. Market participation remains weak, and recovery firms struggle to cover treatment costs.

Residential renovation lacks guidance on separate disposal and financial incentives. Renovation waste is consequently mixed with other waste, discarded indiscriminately, or placed in municipal-waste streams. Its dispersed generation, complex composition, and irregular timing also complicate collection, transport, and recovery. Most cities still rely on mixed collection and transport. Low recovery rates waste resources and increase pressure on urban landfill sites.

Equipment for higher-value processing of recycled building materials is expensive, and dedicated subsidies for recovery investment are unavailable. Recovery returns are much lower than those from conventional landfilling. The absence of special subsidies and green-finance support further undermines the viability of recovery firms. If this persists, conventional unsorted landfill disposal will be difficult to reverse. The recovery supply chain will develop slowly, preventing a life-cycle link between source reduction and final-stage recycling.

5.2. Recommendations

Institutional improvements are proposed to refine construction solid waste management frameworks and enforce extended producer responsibility (EPR). Clear recycling obligations ought to be assigned to manufacturers of construction materials and construction contractors. To address low

recycling efficiency for renovation waste, municipal authorities may launch resident reservation channels for waste collection and transportation, set up temporary on-site storage spaces within communities, and distribute standardized guidelines for classified disposal. Local governments can introduce targeted subsidies for high-value waste recycling technologies, alongside tax incentives and green financing tools to cut operational expenses for recycling enterprises. Cities may also deploy digital zero-waste urban platforms built on blockchain traceability systems to lower administrative supervision costs. Blockchain generates distributed, tamper-proof records that restructure traditional waste management workflows. Such digital tools deliver transparent full-process monitoring, bringing simultaneous environmental and economic benefits to construction waste management systems [7].

Taking Zero-waste-city in East Africa as an example, their policy path adopts three main criteria. First, geographical proximity and regional integration. Second, reported evidence of municipal solid-waste management problems and preliminary continuing education interventions. Third, the existence of peer review and grey literature from 2013 to 2024. These three aspects help the transition to zero-waste cities in the wider East Africa region [8]. The simultaneous advancement of institutional incentives and monitoring management can significantly improve the efficiency of solid waste management.

From the perspective of social participation, a multi-party governance model should be constructed. At the community level, a points-based system for waste sorting should be promoted to increase residents' enthusiasm for participating in the sorting and disposal of construction waste. Simultaneously, collaborative innovation between industry, academia, and research should be carried out, a solid waste treatment technology incubation fund should be established, and the industrialization of university research results should be promoted to fundamentally reduce the technological costs of high-value utilization [9].

Taking Deaw Sub-district in Saraburi Province, Thailand as a case study, this research explores an integrated and sustainable systemic approach to solid waste management based on community participation. The study developed two models: a resident-participation sorting model and a community waste-bank model. One is the municipal solid waste, which sets standards for evaluating management efficiency, monitors the entire process, and dynamically adjusts control measures. The other is the community waste bank model. It defines operational evaluation standards, monitors the entire process, adjusts control measures promptly, and resolves conflicts related to revenue distribution [10].

6. Conclusion and outlook

6.1. Conclusion

Solid waste affects the environment throughout a building's life cycle, but the mechanisms of impact and governance priorities differ by stage.

Planning and design are the first line of construction-waste governance. Green and recycled materials, modular design, and design for disassembly can prevent waste and raise the prospects for later recovery. Construction is the point at which waste generation is most concentrated. Separate collection and on-site recovery can improve recovery at this stage. Demolition is critical for higher-value reuse. Intelligent sorting and higher-value recycling can turn construction waste into useful recycled products and promote circular use of resources.

6.2. Outlook

China still faces major barriers to life-cycle management of construction solid waste. The central barrier is the structural weakness of institutional incentives. Recovered building materials often cost more than natural raw materials. Firms therefore lack motivation to participate, and waste management continues to be treated as a cost burden instead of an activity that can generate economic value.

Future action should strengthen the policy system for solid-waste governance, establish a sound producer-responsibility system, and expand support for construction-waste recovery. These steps can lower recovery firms' costs and improve their returns.

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