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Strategies for effective reuse of waste from abandoned buildings under sustainable development

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Introduction: In the continuous advancement of urbanization, abandoned buildings are a huge challenge in achieving sustainable development goals. If these legacy buildings are not properly handled, they will cause a huge burden on society, economy, and the environment. Based on the material flow analysis method, an evaluation index system was constructed for legacy building resources, and a systematic study was conducted on the reuse pathways of their waste.

Methods: This study focuses on the material flow, reuse pathways, and resource utilization strategies of legacy construction waste, aiming to improve the reuse efficiency of waste building materials and promote the achievement of sustainable development goals. In the study, indicator design was used to quantify the obstacles to the reuse of legacy construction waste, and social and economic costs were analyzed to ensure the comprehensiveness and scientificity of the research.

Results: The experimental results show that the waste recycling rate under the implementation of this strategy reached 82.7%, and the resource utilization rate increased by 50.1%. For the obstacles to the reuse of construction waste, the network density reaches 0.052, and the overall network structure shows a lack of concentration, indicating that the current management methods for construction waste reuse have further optimization space.

Discussion: The study effectively promotes the sustainable utilization of legacy buildings in cities, which is of great significance for improving the quality of urban space and promoting sustainable social development.

KEYWORDS

sustainable development, material flow, reuse pathways, abandoned buildings, indicator design

1 Introduction

Abandoned buildings not only solidify historical moments, but also have strong reuse value in modern urban development (Zou and Wang, 2021). In the global wave of sustainable development, the reuse strategy of abandoned buildings has become particularly important. The effective reuse of construction waste, as a byproduct of urban development, is directly related to the substantive progress of sustainable development and the closed-loop of resource recycling (McAtackney, 2022; Xu et al., 2024). Research on the material flow of construction waste can reveal its resource potential and environmental impact. The refined management of these material flows is a prerequisite for achieving the reduction and resource utilization of construction waste (Glatt et al., 2021). The reuse approach of abandoned buildings involves specific methods of converting waste into building materials or other functional products, with the significance of endowing abandoned buildings with new vitality (Dixit et al., 2022; Shooshtarian et al., 2022). The resource utilization strategy for abandoned buildings is a macro concept that encompasses the entire process from policy formulation to technological application, aiming to optimize the reuse efficiency of abandoned buildings, reduce environmental loads, and promote coordinated development of the economy, society, and environment. Under the background of the rapid development of urbanization, the management practice of construction and demolition waste faces many challenges, among which how to efficiently reuse the remaining construction waste, reduce the impact on the environment, and achieve resource conservation and sustainable development has become a key issue to be solved. In response to this problem, the study aims to explore and solve the following research questions: 1) What deficiencies exist in current management practices of legacy construction waste, resulting in inefficient resource recovery and reuse? 2) How to identify and quantify the obstacle factors in the recycling process of legacy construction waste through a systematic method? 3) Based on material flow analysis, how to construct an effective recycling strategy for legacy construction waste to improve recycling efficiency? In order to solve the research problems, the objectives set by the research are as follows: 1) To establish a comprehensive evaluation index system to evaluate the recycling potential of the construction waste. 2) Systematically analyze the generation, collection, transportation and treatment process of construction waste through material flow analysis method. 3) Identify and quantify the main obstacles affecting the reuse of legacy construction waste, and propose targeted improvement measures.

The study is divided into four parts. The first part provides a brief overview of sustainable development strategies and the reuse of abandoned buildings. The second part elaborates on the utilization strategies of construction waste under sustainable development, including material flow analysis of construction waste, analysis of reuse barriers, and construction of waste resource utilization strategy. The third part validates the research method, including material flow analysis, networked analysis of obstacles to the reuse of abandoned buildings, and the effectiveness of the reuse strategy model. The fourth part is a summary, and outlook of the research content. The research technology roadmap is shown in Figure 1.

2 Related works

In the construction industry of modern urban development, sustainable development strategy requires a certain level of environmentally friendly materials, energy saving and emission reduction technologies and renewable energy. These methods can mainly reduce the life cycle cost and ecological footprint of buildings, thus promoting environmental protection and efficient use of resources. Some scholars have conducted relevant research on the construction engineering under the sustainable development strategy. Q. Li provided guidance on the direction of green building design based on climate friendly ideas for sustainable architectural design. Green Finance refers to financial activities that support environmental objectives such as environmental improvement, climate change mitigation and resource efficiency. It proved the effectiveness of green finance in supporting climate change adaptive design (Li, 2023). Feng et al. (2021) proposed a bi-directional green promotion framework for the application of 6G and AI technologies in green development. Two-way green promotion framework refers to the mutual promotion and common development of technologies through the integration of green technologies and emerging technologies such as 6G and artificial intelligence in the process of technology development and application. Studies have shown that this framework effectively promotes the promotion of sustainable development strategies (Feng et al., 2021). Hammond et al. (2021) proposed a multi-perspective integration theoretical model to address the low adoption rate of green buildings. The multi-perspective fusion theoretical model is a systematic analysis method that combines perspectives and theories from different disciplines to comprehensively analyze the low adoption rate of green buildings. The systematic analysis of its promotion obstacles was achieved, providing direction guidance for sustainable development (Hammond et al., 2021). Pham et al. (2023) investigated the impact of transformational leadership on sustainable development needs in the construction supply chain and developed a sustainable development supply chain framework based on transformational leadership, achieving a sustainable development strategy in the supply chain. The study demonstrated the effectiveness of the improved framework (Pham et al., 2023). Chakravarthy et al. (2022) conducted a study on management barriers and practices in sustainable development of construction projects. The sustainable development management process of construction projects was optimized, achieving a comprehensive analysis of obstacles and best practices in construction project management. The study identified obstacles and promoted the further application of sustainable development strategies in construction projects (Chakravarthy et al., 2022). Wang et al. (2024) analyzed resources for sustainable development in the construction industry. A new resource utilization framework based on competitive relationships was proposed, achieving a deep understanding of the competitive relationships in resource utilization that supported green and low-carbon transformation. Its importance in promoting sustainable development and transformation in the industry was verified (Wang et al., 2024).

In the process of urban construction and renewal, there are a large number of legacy buildings, which have various materials and Spaces that can be reused. Efficient reuse of legacy buildings can reduce environmental damage and waste of resources, thereby supporting sustainable development. Some scholars have also conducted relevant research on architectural reuse. M. A. T. Alsheyab analyzed the impact of construction waste recycling from the perspective of construction and demolition waste recycling, evaluated its impact on climate change and sustainable development, and proved that recycling activities have A positive effect on reducing environmental deterioration (Alsheyab, 2022). Umar et al. (2021) evaluated the effectiveness of implementing construction and demolition waste management practices in Malaysia, targeting the reuse management practices

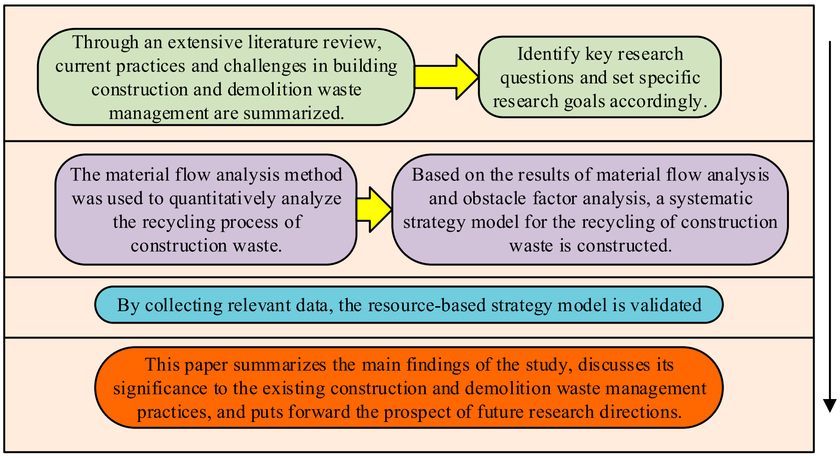

FIGURE 1
Technology roadmap.

of abandoned buildings in Malaysia. It proved the contribution of these practices to improving resource utilization and environmental protection (Umar et al., 2021). Whittaker et al. (2021) conducted in-depth research on the methods and uses of building reuse and demolition waste to improve the efficiency of abandoned building reuse. A comprehensive solution was proposed, effectively improving its reuse efficiency. The research demonstrated the effectiveness of this innovative treatment method in promoting the reuse and recycling of abandoned buildings (Whittaker et al., 2021). J. Liu proposed a policy support policy based on tax incentives to address the lack of economic benefits for enterprises in the reuse of abandoned buildings. It realized the economic benefit analysis of abandoned building reuse projects under tax incentives. Tax incentives could significantly enhance the economic benefits of recycling and reusing abandoned buildings (Liu et al., 2022). Lamba et al. (2022) studied the recycling of plastic waste in abandoned buildings based on sustainable development principles. The impact of plastic waste on the sustainable development and utilization of building materials was evaluted. This recycling and reuse had a positive impact on environmental and social sustainability (Lamba et al., 2022). Marinho et al. (2022) conducted a comprehensive analysis of the reuse and recycling practices of construction and demolition waste in Portugal. The current situation of the management practices for the reuse of abandoned buildings in the country was thoroughly evaluated, providing reference and technical support for specific practices in the reuse of abandoned buildings (Marinho et al., 2022). In order to improve the reliability of reuse of legacy buildings, J. Duan et al. (2021) proposed an ICA-XGBoost model to achieve accurate prediction of compressive strength of recycled aggregate concrete, which has been proved to be of great value in improving the use efficiency of recycled materials (Duan et al., 2021).

Some scholars have conducted relevant research on construction waste management. Liu et al. (2021), aiming at the circular economy problem in construction waste management, proposed a method combining social network analysis. In the process, the management mechanism and effect of chemical recycling were analyzed with Guangzhou as the main research area. This study provides theoretical guidance for the transformation of the construction industry from recycling to energy conservation (Liu et al., 2021). Liu J and his research team proposed a combined sorting model for the management and control of urban construction waste. In the process, the relationship between unused construction waste and carbon emissions is explored, and the carbon emission effects of different policies are collected. The experimental results provide technical support for the government to introduce construction waste management models and policies (Liu et al., 2023). Aiming at the sustainable development of the construction industry, Wang Z and other scholars put forward a method using the environmental Kuznets curve. In the process, carbon emissions of 30 provinces in China were extracted and the relationship between them and economic growth was analyzed. The experimental results provide data support for construction waste management (Wang et al., 2023).

Although existing studies have extensively explored multiple aspects of reuse of legacy buildings, including resource utilization, environmental impact assessment, and economic incentive policies, most studies focus on single-dimensional analysis, lacking systematic consideration of the whole life cycle of legacy buildings. In addition, the research on the strategy of recycling construction waste in the existing literature mainly focuses on the technical and policy aspects, while the comprehensive analysis of market mechanism and social and cultural factors is insufficient. Therefore, the paper proposes an efficient reuse strategy for legacy buildings based on sustainable development goals. Through in-depth analysis of the entire life cycle of buildings from construction to demolition, combined with existing policies and regulations, the paper analyzes the reuse obstacles of legacy buildings, and proposes targeted reuse strategies for legacy buildings. Through the implementation of these strategies, it is expected to open up new ways for the use of legacy buildings, improve their economic and environmental benefits, and contribute to the sustainable development of the city, so as to achieve multi-win social, economic and environmental benefits.

3 Reuse strategies for abandoned buildings under sustainable development

To effectively combine sustainable development goals with the reuse of abandoned buildings, a comprehensive three-step strategy is adopted in the study. Firstly, regarding the entire lifecycle of abandoned buildings, the waste material flow is analyzed. Identifying the resource consumption and generated waste in these processes can reveal potential opportunities for resource conservation and waste reduction. Then, based on existing regulations and policies, the obstacles to the reuse of abandoned buildings are analyzed. These obstacles have been systematically analyzed, aiming to find breakthroughs and develop targeted strategies for the reuse of abandoned buildings. Finally, the resource utilization strategy model for abandoned buildings is constructed. Based on the analysis results of the first two steps, a systematic reuse strategy and measures are designed to maximize the reuse of abandoned buildings, thereby implementing the circular economy.

3.1 Material flow analysis of abandoned construction waste

The waste generated during the demolition and renovation process of abandoned buildings may include recyclable materials and substances that pose potential hazards to the environment. To achieve efficient utilization of abandoned building resources and sustainable environmental development, based on the entire lifecycle of abandoned buildings, a material flow analysis of abandoned building waste is conducted, including the construction and demolition stages of the buildings. During the construction phase, the utilization efficiency of raw materials and the proportion of waste generated during construction are analyzed. In the demolition stage, the focus is on analyzing the waste material flow generated during the dismantling of the building structures and non-structural parts. Based on the data of new construction projects in a certain region from 2022 to 2023, data collection and model calculation are used to estimate the proportion of waste in different life cycle stages. The proportion of waste generated during building demolition and construction is shown in Figure 2.

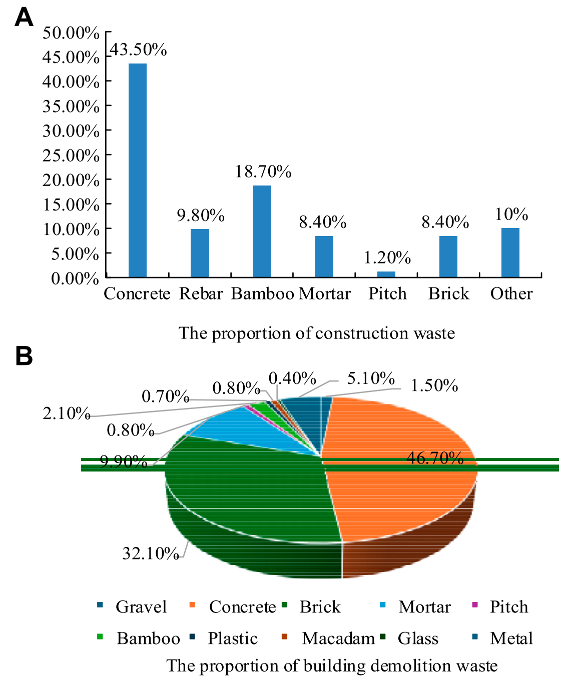

FIGURE 2
Schematic diagram of the proportion of construction and demolition waste. **(A)** The proportion of construction waste **(B)** The proportion of building demolition waste.

Figure 2 shows the proportion of various components of waste generated during construction and demolition of buildings. During the construction phase, the proportion of waste varies from high to low, including cement, waste bamboo and wood, asphalt, steel bars, mortar, and bricks. This is because cement is one of the most commonly used materials in the construction, which is used in the production of concrete, masonry and other processes. Waste bamboo and wood come in second place, mainly from temporary facilities such as templates and scaffolding. The proportion of asphalt, steel reinforcement, mortar, and bricks is relatively low, but they are also indispensable materials in the construction process. In the stage of building demolition, the proportion increases from high to low, and the waste is concrete, bricks, mortar, metal, plastic, crushed stone, etc. In the stage of building demolition, the proportion of waste from high to low is concrete, bricks, mortar, metal, plastic, crushed stone, etc. The proportion of concrete is the highest, because concrete is the main constituent material of modern buildings. A large amount of concrete waste is generated during the demolition process of buildings. The proportion of waste bricks and mortar is also relatively high, which is related to the construction of the building (Oh, 2023). The materials such as metals, plastics, and crushed stones are relatively low, but they are also common materials in buildings (Ma et al., 2023). After analyzing the composition of construction waste, it can be found that there are various types and huge quantities of waste generated during the construction and demolition. If these wastes are not properly handled, they will cause serious pollution to the environment. Therefore, this study further conducts material flow analysis on the reuse of abandoned construction waste. Based on the different types of materials, they are classified into inorganic non-metallic materials, organic non-metallic materials, and metal materials. Then a framework for the material flow of abandoned building resource utilization is constructed. For inorganic non-metallic materials, physical methods such as crushing, screening, and cleaning can usually be used for pretreatment, and then converted into secondary materials suitable for new construction projects according to specific technical requirements (Shao et al., 2022). The reuse process of waste metal materials is relatively complex. For example, bamboo and wood, after being crushed and sliced, are used to make artificial boards or as biomass fuel. Plastic can be processed into new plastic products through thermoplastic processing (Lu et al., 2022). Figure 3 shows the constructed material flow framework for the resource utilization of abandoned buildings, as well as an example of the reuse of waste concrete.

Figure 3 shows the constructed material flow framework for the resource utilization of abandoned buildings, as well as an

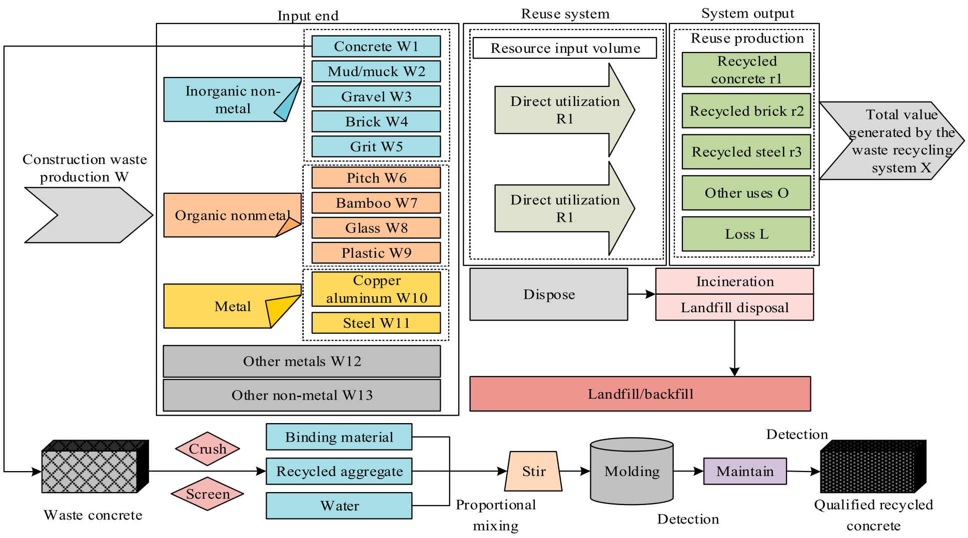

FIGURE 3
Schematic diagram of recycling process of recycled material flow frame and waste concrete for abandoned buildings.

TABLE 1 Explanation of material flow analysis and calculation formula of abandoned buildings.

No.	Index	Formula	Detail
1	System balance accounting	$System\,balance = \sum_{i=1}^{13} W_i = O + L + \sum_{i=1}^{3} r_i + C$ (1)	The input to the system is equal to the output
2	Waste production volume (W)	$W = \sum_{i=1}^{13} W_i$ (2)	
3	Reuse system waste input volume	$R1 + R2$ (3)	Mainly equal to the amount of reuse plus recycling
4	Recycling system waste recovery rate	$\frac{(R1+R2)}{\sum_{i=1}^{13} W_i}$ (4)	Mainly related to waste inventory and waste production
5	Total value generated by the waste recycling system (X)	$\sum_{i=1}^{3} r_i + O$ (5)	Mainly related to rebio yield and other uses
6	Total material output	$\sum_{i=1}^{3} r_i$ (6)	Mainly related to rebio yield
7	Reuse system loss rate	$\frac{L}{R1+R2}$ (7)	Mainly associated with mass loss level resource utilization system
8	Productivity of construction waste	$\frac{\sum_{i=1}^{3} r_i}{R1+R2}$ (8)	Related to the total value of the system and the amount of input
9	Regional construction waste production intensity	$\frac{W}{Gross\ regional\ product}$ (9)	
10	System waste conversion efficiency	$\frac{\sum_{i=1}^{3} r_i}{R1+R2}$ (10)	Related to the amount of material output and input
11	Reuse rate of construction waste	$\frac{\sum_{i=1}^{3} r_i}{\sum_{i=1}^{13} W_i - W2}$ (11)	Related to actual recycled product weight and waste production, mud/muck is not considered

example process for the reuse of waste concrete. Among them, waste concrete is first crushed and screened to obtain recycled aggregates, then added with cementitious materials and water, and mixed and stirred in proportion to form. After passing the test, recycled concrete with useable value can be obtained (Nagalli et al., 2021; Usman and Abdullah, 2023). To refine the material flow analysis of abandoned buildings and further calculate their main indicators in detail, the specific calculation formulas and explanations are shown in Table 1.

In Table 1, all variables correspond to Figure 3. Among them, W_i represents the corresponding waste. r_i represents recycled products. L represents loss. C represents backfilling, In material flow analysis, backfilling refers to the process of reusing construction waste, where a portion of the material may not be directly used for new construction projects or other purposes due to various reasons, but instead be used to backfill the land, which usually occurs at construction sites or other places (Gao et al., 2021). By calculating the backfill rate, it is possible to understand the proportion of materials in the reuse system that are not effectively utilized but are treated as waste. X represents the total value generated by the waste recycling system. $R1$ represents direct utilization. $R2$ represents indirect utilization. $\sum_{i=1}^{13} W_i$ represents the sum of the masses of 13 types of waste. $\sum_{i=1}^{3} r_i$ represents the sum of the quality of the three recycled products. Material flow analysis of abandoned buildings can comprehensively understand the types, quantities, and potential value of materials contained within them. The results of material flow analysis can provide important basis for the reuse plan of abandoned buildings. Mastering information on the types, quantities, and quality of recyclable materials can develop targeted recycling plans, and select appropriate recycling pathways and processing techniques. Then, to further improve the efficiency and effectiveness of the reuse of abandoned buildings, an analysis is conducted on the obstacles that may be encountered during the reuse process.

3.2 Analysis of obstacles to the reuse of abandoned buildings

To fully evaluate the obstacles to the reuse of abandoned buildings, this study conducts a semi-structured analysis based on current literature, starting from stakeholders. Firstly, through a systematic review of existing literature, it is possible to comprehensively understand the research status and progress of the reuse of abandoned buildings, thereby identifying the key influencing factors in the process of reuse of abandoned buildings (Gao et al., 2023). Analyzing the content and implementation effects of these policies can identify the advantages and disadvantages of existing policies, and propose targeted improvement suggestions. Once again, the industrial structure and market environment involved in the reuse of abandoned buildings also need to be considered. Understanding the characteristics and interrelationships of each link in the industrial chain can identify the opportunities and challenges faced by the reuse of abandoned buildings, evaluate their commercial feasibility and promotion prospects. This analysis specifically includes government, design units, material suppliers, construction units, transportation units, demolition units, resource reuse enterprises, waste landfills, research institutes, and the public. The specific obstacles to the reuse of abandoned buildings are shown in Table 2.

A comprehensive and systematic analysis of the obstacles to the reuse of abandoned buildings can identify specific problems at multiple levels, including regulations, economy, technology, and socio-culture. Then, to effectively promote the resource utilization of abandoned buildings and fully tap into their social, cultural, and economic potential, this study further constructs a strategy model for the resource utilization of abandoned buildings.

3.3 Construction of resource utilization strategy model for abandoned buildings

To promote the efficient reuse of abandoned building resources, considering the increasingly severe global problems such as resource depletion and environmental pollution, combined with the analysis of material flow and reuse obstacles of abandoned buildings, a strategy model for the resource utilization of abandoned buildings is constructed. Based on the principles of resource conservation and environmental friendliness, the fundamental difference between traditional linear economy ("take-make-use-waste" model) and circular economy (emphasizing resource regeneration and recycling) is considered. To promote sustainable development, a strategy model for resource utilization of abandoned buildings based on circular economy is constructed. Figure 4 shows the process of traditional linear economy and circular economy.

Figure 4 shows the process of traditional linear economy and circular economy. The main difference between traditional linear economy and circular economy lies in the utilization and processing mode of resources. In the traditional linear economic model, the resource follows a unidirectional order of "extraction-manufacturing-use-disposal". This model has led to the consumption and waste of a large number of resources, environmental pollution and permanent loss of resources. In the circular economy, the principle of "reduction-reuse-recovery-regeneration" is mainly followed. It breaks through the traditional linear economic model, emphasizing the maximization of resource utilization and circular reuse throughout the entire industrial chain. The effective recycling and reuse of resources are considered in the product design stage. After the end of the product's service life, resources can be reused through remanufacturing, repair, or recycling, forming a closed-loop system to minimize resource loss and environmental impact. Therefore, the study combines circular economy to construct a business model for the resource utilization of abandoned buildings, as shown in Figure 5.

As shown in Figure 5, in order to promote the resource utilization of construction waste in the circular economy system, overcome obstacles such as logistics, costs, and regulations, an innovative business model has been proposed. Enterprises should establish cooperation with all parties in the supply chain, including transportation, equipment supply, scientific research and construction units, to ensure raw material supply, reduce costs, promote technological innovation, and sell recycled products. At the same time, by creating interdisciplinary R&D departments and combining academic, industrial, and government resources, we promote knowledge transfer and technological progress. Promote prefabricated buildings to achieve rapid material recycling and closed-loop utilization. Utilize information platforms such as BIM to achieve data sharing and quantitative management of the entire industry chain. Provide cost-effective products for different market segments while creating social value, including land conservation, environmental protection, environmental awareness enhancement, and promoting industrial development. Adopt customized cooperation and marketing strategies, such as strategic alliances, public-private partnerships, and point discounts, to maintain customer relationships. To ensure the effective reuse of abandoned buildings and achieve maximum resource utilization, promote sustainable environmental development, and respond to the concept of circular economy, promote a win-win situation between economic benefits and environmental protection, the reuse and promotion strategy

TABLE 2 Details of barriers to reuse of abandoned buildings.

Related object	Serial number	Obstacle factors	Related object	Serial number	Obstacle factors
Government	G1	Lack of regulation	Transportation enterprise	T2	Lack of control
	G2	Lack of commitment		T3	Lack of circularity
	G3	Lack of vision	Demolition enterprise	E1	Lack of site supervision
	G4	Lack of data		E2	Lack of sort processing
	G5	Lack of quality standards		E3	Lack of circularity
	G6	Lack of regulation	Reuse enterprise	R1	Lack of raw materials
	G7	Lack of usage rules		R2	Invalid processing
	G8	Lack of policy support		R3	Equipment limitation
	G9	Lack of publicity		R4	Blind production
	G10	Lack of official demonstration		R5	Lack of integration strategy
Architect	D1	Lack of green design		R6	Fund shortage
	D2	Lack of circularity		R7	Excessive cost
Material supply	M1	Lack of production responsibility		R8	Size limitation
	M2	Lack of circularity		R9	Unreasonable price
Construction unit	C1	Lack of reuse		R10	Higher admission fees
	C2	Lack of recycled product quality		R11	Unreasonable site selection
	C3	High regeneration cost		R12	Lack of publicity
	C4	Lack of circularity	Landfill	L1	Space problem
Construction organization	O1	Lack of construction standards		L2	Lack of circularity
	O2	Lack of recycling	Scientific institute	S1	Funding problem
	O3	Exorbitant cost		S2	Lack of research
	O4	Lack of sort processing		S3	Lack of cycle planning
	O5	Lack of regeneration		S4	Lack of loop optimization
	O6	Lack of recycled product quality		S5	Lack of research on barriers
	O7	Excessive regeneration price	The public	P1	Lack of quality recognition
	O8	Lack of regeneration		P2	Biased primary material
Transportation enterprise	T1	Direct landfill		P3	High regeneration price

of abandoned buildings has been deeply analyzed. Therefore, starting from the three main subjects, the study analyzes the promotion strategies for the reuse of abandoned buildings, as shown in Figure 6.

Based on the analysis of the reuse of abandoned buildings, to effectively promote the recycling of resources, improve environmental quality, stimulate economic vitality, and ensure the protection and inheritance of cultural heritage, this study combines

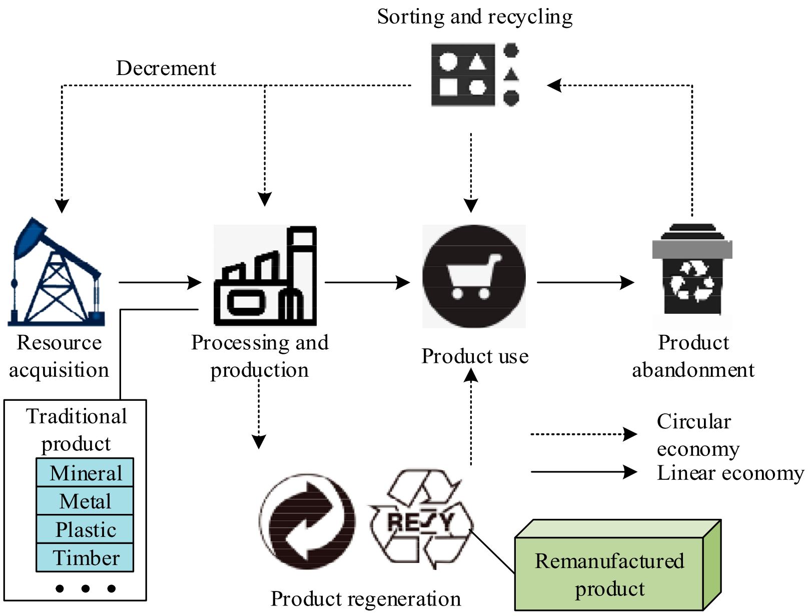

FIGURE 4
Schematic diagram of traditional linear economy and circular economy process.

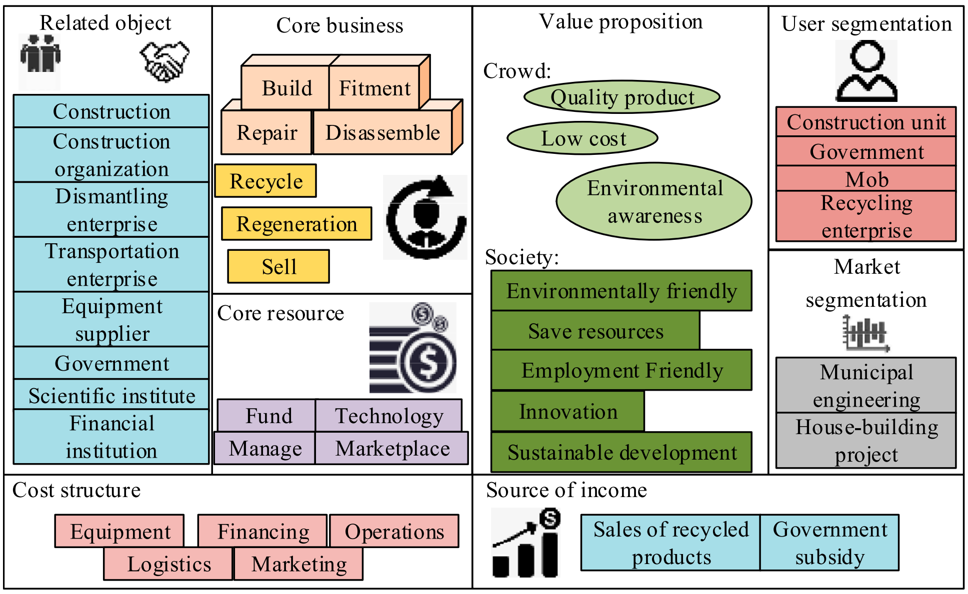

FIGURE 5
Schematic diagram of the business model of recycling of abandoned buildings.

the perspective of the government to construct a phased strategy model for the reuse of abandoned buildings. It is specifically divided into production stage, recycling stage, reuse stage, and promotion and use stage. The specific reuse strategy model for the constructed abandoned buildings is shown in Figure 7.

Figure 7 shows a strategy model for the reuse of abandoned buildings. The goal of the strategic model is to achieve efficient recycling and reuse of construction waste, reduce the impact of waste on the environment, and transform it into valuable resources. Firstly, in the production stage, the main sources of waste are construction, demolition, and decoration. After on-site classification and sorting, it enters the recycling stage and arrives at the landfill and resource utilization enterprises through transportation enterprises. In the recycling stage, with the support of equipment manufacturers, research institutes, and testing institutions, renewable resource products are produced. Finally, it is transported to the construction unit, and the public. The reuse of residual construction waste is completed.

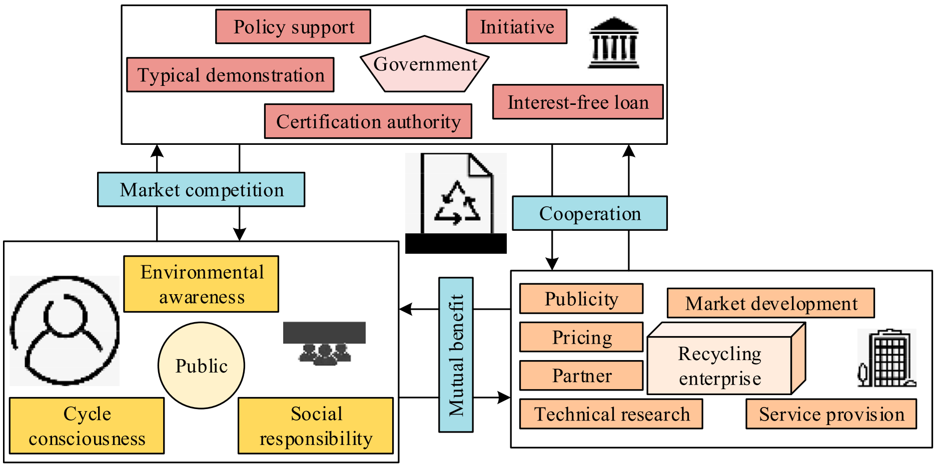

FIGURE 6
Analysis diagram of the reuse and promotion strategy of abandoned buildings based on the three main bodies.

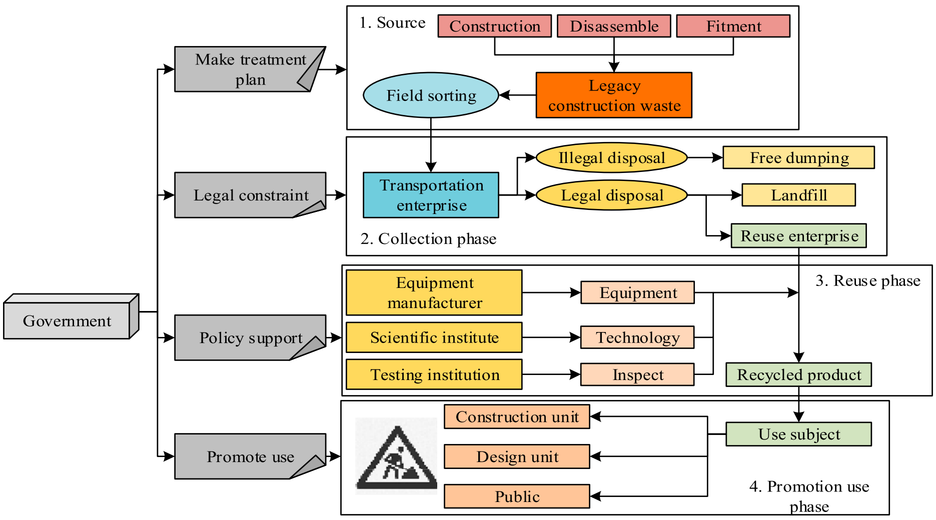

FIGURE 7
Schematic diagram of reuse strategy model for abandoned buildings.

4 Verification of the resource utilization strategy model for construction waste

4.1 Material flow analysis of abandoned construction waste

To better understand the potential of the flow and recycling of leftover construction waste, considering the limited resources and environmental protection needs, this study conducts material flow analysis of leftover construction waste based on the principles of circular economy. To obtain the data, statistical data and official reports published by government agencies and construction industry associations were collected. Through on-site research, first-hand data were obtained directly from construction sites, waste treatment centers and recycling enterprises, including the types, quantities and disposal methods of waste. Through literature review, academic studies, case studies and theoretical models related to construction and demolition waste management are collected, which provide theoretical basis and empirical data from previous studies. The collected data will be integrated and cross-verified to ensure the consistency and accuracy of the data, and then the statistical analysis method is used to conduct in-depth analysis of the data. The professional SubStance Flow Analysis software is used to analyze the flow in construction waste systems. Based on the constructed classification system above, statistical analysis is conducted on the flow of waste at different treatment stages. A detailed analysis of the material flow of construction waste is shown in Figure 8. From Figure 8, there was significant room for optimization in the current reuse pathways of construction waste.

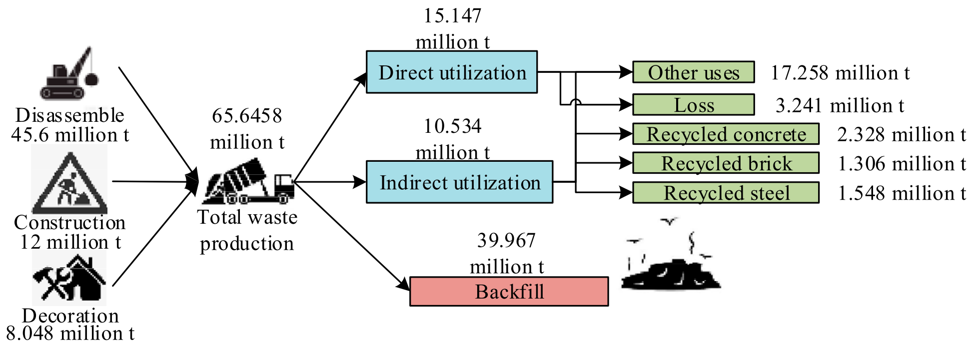

FIGURE 8
Schematic diagram of material flow analysis of construction waste.

Based on the above analysis, it is possible to conduct a thorough analysis of the material flow of construction waste. On this basis, effective management strategies are formulated to improve resource recycling and minimize environmental impact.

4.2 Network analysis of recycling barriers for abandoned construction waste

This study further delves into the problems and potential improvement opportunities in the recycling network of construction waste. Considering the complex relationships and interactions among participants in the network, Ucinet6 software is used to conduct a detailed quantitative analysis for the network indicators of obstacles to the recycling of construction waste, and to visualize the network relationships. The first step in conducting centrality analysis on Ucinet6 is to ensure that network data is correctly imported into Ucinet6, and necessary cleaning and formatting have been carried out. Secondly, select appropriate centrality indicators based on the research objectives. Then, select the corresponding command or tool in Ucinet6 to perform centrality analysis. At the same time, analyze the results of centrality indicators and identify key obstacles in the network. Finally, use Ucinet6's visualization tools to display the analysis results, helping to intuitively understand the network structure and the role of obstacles.

Ucinet6 quantifies the importance and influence of various obstacles in the network by calculating indicators such as degree centrality, proximity centrality, and betweenness centrality. Degree centrality determines the influence of nodes based on their number of connections, and is applicable to both undirected and directed graphs; Proximity centrality measures the average distance between a node and all other nodes in the network, reflecting the speed of information dissemination; Quantify the intermediate frequency of nodes in the shortest path of the network based on betweenness centrality, and identify the role of bridges; PageRank is based on the random walk algorithm, considering the link relationships and importance transfer between nodes. As shown in Table 3.

Table 3 shows the degree centrality, proximity centrality, betweenness centrality, and PageRank values of obstacles, all presented to two decimal places. The cost issue scored 0.41 on degree centrality, indicating a significant direct connection with other obstacles in the network. The betweenness centrality of regulatory restrictions is 0.52, indicating its pivotal role in information flow. The PageRank value for the cost issue is 0.52, confirming its importance in the network. Although the market acceptance score is 0.24 in terms of degree centrality, its PageRank value of 0.32 indicates that its influence cannot be ignored. In Figure 9, the network analysis of the obstacles to the recycling of construction waste is presented. From Figure 8, the five obstacles with high centrality are O5, C1, R1, T1, and O4, respectively, from high to low. Among them, O5 indicates a lack of reuse awareness in construction organization. C1 refers to the lack of direct reuse by the construction unit. R1 indicates a shortage of raw materials in the recycling industry. T1 is the direct landfill behavior of transportation enterprises. O4 indicates a lack of classification in construction organization.

Then, to further identify and understand the key obstacles and their interactions that affect the recycling process of construction waste resources, the centrality values of each obstacle factor are tested and analyzed. Centrality analysis is an important social network analysis indicator that can be used to evaluate the importance of a node in a network. A high centrality indicates that it can have a greater impact on the overall information flow of the network. The test results are shown in Figure 10. From Figure 10, the center value of O8 was the highest, far greater than the second ranked node. C1 and O2 were second. In practice, the focus should be on analyzing O8, which is the lack of reuse behavior in construction organization.

To effectively solve the problems in the recycling process of construction waste resources and optimize the efficiency of the entire system, based on the obtained data, the correlation between obstacle factors is calculated. Obstacle factors are subjected to network clustering. Network clustering can help identify groups of obstacle factors with similar features or strong correlations, thereby providing strategic basis for the structural optimization and obstacle removal of the entire resource recovery network. The study conducted correlation analysis on 54 obstacles to the resource utilization of construction waste using the CONCOR program of Ucinet software, and then implemented clustering processing. This process divides obstacle factors into eight different groups based on the similarity of network structure. The equivalence of the positions of obstacle factors within each group in the network indicates that they are structurally similar.

TABLE 3 Centrality analysis data.

Obstacle name	Degree centrality	Proximity centrality	Betweenness centrality	PageRank
Regulatory restrictions (A)	0.37	0.68	0.52	0.47
Technical limitations (B)	0.28	0.59	0.39	0.35
Cost issue (C)	0.41	0.71	0.63	0.52
Lack of awareness (D)	0.34	0.64	0.47	0.41
Market acceptance (E)	0.24	0.56	0.29	0.32

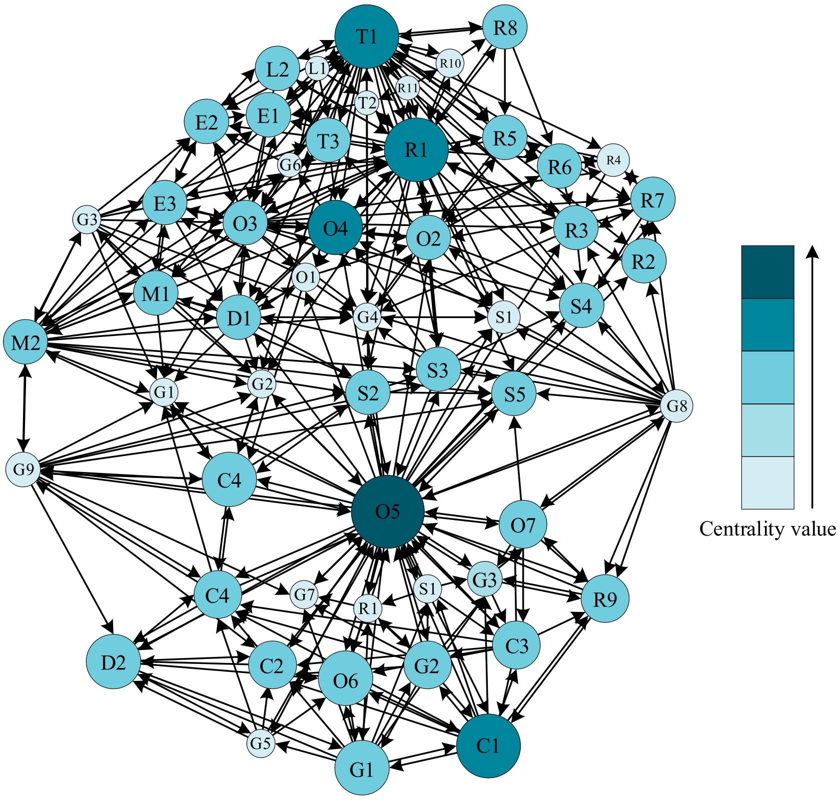

FIGURE 9
Network analysis of barriers to recycling of abandoned construction waste.

The specific clustering of obstacle factor networks is shown in Table 4.

To further understand the distribution and overall impact of obstacle factors in the recycling of construction waste resources, based on the completed network clustering, Ucinet 6 software is used to analyze the density matrix of obstacle factors. The density matrix of obstacle factors is shown in Table 4. From Table 4, the correlation between Zone B and Zone C was the highest, followed by Zone B and Zone D. Meanwhile, the network density was 0.052, but the concentration was insufficient. The Ucinet software automatically calculates key indicators such as network density, and users only need to input network data. In this study, the software determined a network density value of 0.052, indicating that the actual number of edges is much lower than the potential maximum value, indicating that the network structure needs to be optimized and may lack centralized coordination. To gain a deeper understanding of this value, it should be compared to the density values of other networks in the literature: a high-density value close to 1 indicates a concentrated network, while a low-density value indicates loose network connections. The low density value of this study reflects that although there are connections between nodes, the overall connectivity is insufficient, which may weaken the information flow and coordination efficiency of building waste resource utilization. The density matrix of specific obstacle factors is detailed in Table 5. The density matrix of obstacle factors is shown in Table 5.

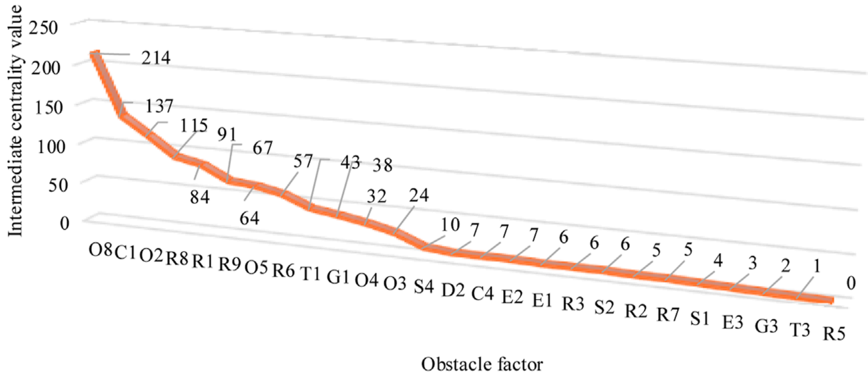

FIGURE 10
Centrality analysis of barriers to reuse of abandoned buildings.

TABLE 4 Network node partition of barriers to reuse of abandoned buildings.

Subzone	Include obstacles
Zone A	G1, G2, G9, G4, G8
Zone B	G7, G5, G10, R12
Zone C	D2, C2, C4, O8, P2, C1, P1, O6, O5
Zone D	R9, P3, C3, O7
Zone E	G6, R11, G3, L1, T2, R10, O1
Zone F	R8, R6, O2, T3, R5, T1, E1, E2
Zone G	O3, L2, O4, RI2, RI3, RI1, D1, E3, M1, M2, RI4, RI5
Zone H	R1, R4, R7, R2, R3

TABLE 5 Network node density matrix of barriers to reuse of abandoned buildings.

-	A	B	C	D	E	F	G	H
A	0.000	0.000	1.262	0.912	0.000	1.142	1.569	0.396
B	0.000	0.000	2.457	1.597	0.000	0.000	0.000	0.000
C	0.000	0.000	0.872	0.099	0.000	0.024	0.049	0.000
D	0.000	0.000	0.821	1.502	0.000	0.000	0.000	0.000
E	0.000	0.000	0.039	0.000	0.000	0.721	0.392	0.357
F	0.000	0.000	0.000	0.000	0.000	0.527	0.069	0.912
G	0.000	0.000	0.000	0.000	0.000	0.129	0.114	0.279
H	0.000	0.000	0.000	0.000	0.000	0.316	0.000	0.668
Network density = 0.052								

To comprehensively evaluate and solve the obstacles in the recycling leftover construction waste, as well as their relative positions and roles in the overall network, the image matrix of the obstacle factor network is further analyzed. The image matrix analysis of obstacle factors is shown in Figure 11. From Figure 11, zones A, B, and E were the core locations, which had a significant impact on the obstacle factor network.

4.3 Analysis of the recycling rate of residual construction waste

To verify the actual effectiveness of the optimization scheme for the recycling of construction waste resources proposed in the research, a quantitative analysis is conducted on the recycling rate based on current data to measure the effectiveness of the optimization measures. The analysis results are shown in Figure 12. From Figure 12, after implementing the optimization scheme, the recovery rate reached 82.7%, indicating that the scheme has substantially improved the resource recovery efficiency of construction waste. In addition, the growth rate of recycling rate also showed a rapid improvement, reflecting the positive driving force of optimization measures in promoting resource recovery. Compared with traditional schemes, the increase in recovery rate reached 67.4%. This significant improvement demonstrates the enormous potential and practical benefits of the optimization scheme.

4.4 Analysis of resource utilization rate of construction waste

To comprehensively evaluate the effectiveness of the optimization scheme in improving the resource utilization of construction waste, a quantitative analysis is further conducted on the resource utilization rate. The analysis results are shown in Figure 13. After implementing the optimization scheme, the resource utilization rate significantly increased to 92.7%, indicating

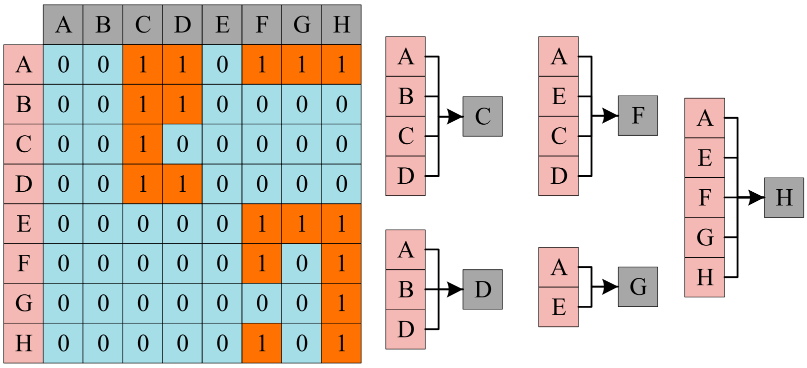

FIGURE 11
Network image matrix of barriers to reuse of abandoned buildings.

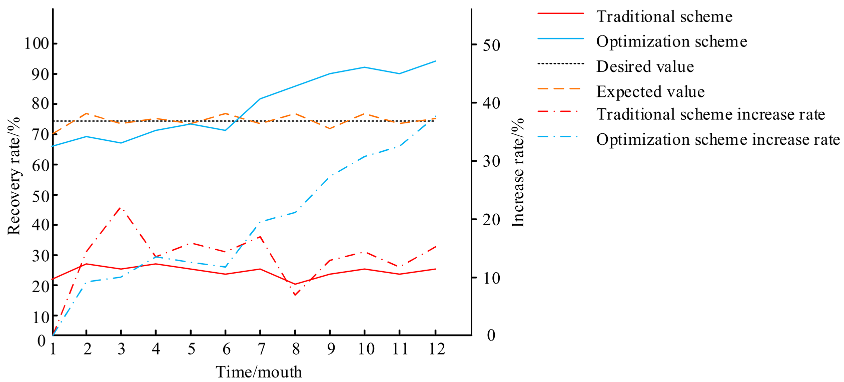

FIGURE 12
Recovery rate test of construction waste.

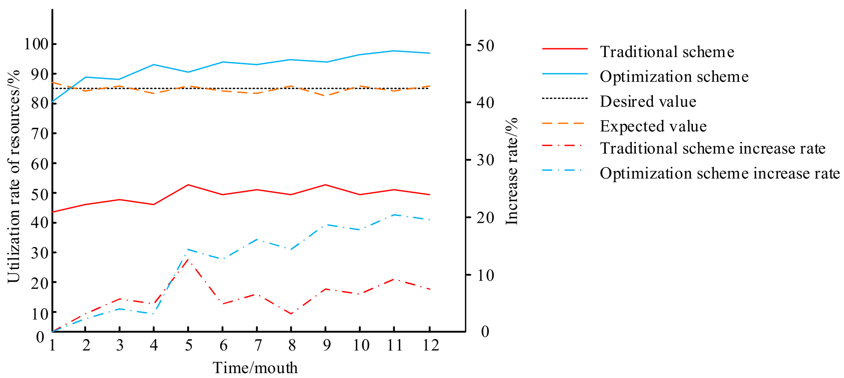

FIGURE 13
Resource utilization test of residual construction waste.

that the plan efficiently converted waste into useful resources. Compared with traditional solutions, it has increased by 50.1%, demonstrating the enormous potential of the optimization scheme in optimizing resource circulation and enhancing environmental sustainability.

4.5 Discussion

The research is supported by the theory of circular economy, which holds that by reducing resource consumption and waste generation, and promoting resource reuse and recycling, economic activities can be sustainable. Through the material flow analysis and the construction of the resource strategy model, the theory of circular economy provides the theoretical basis for the analysis of the construction and demolition waste management practice, and guides the construction of the resource strategy model. The research results show that by optimizing the sorting, collection and treatment of building construction and demolition waste, the maximum utilization of resources and the minimization of environmental impact are achieved, which echoes the multi-perspective fusion theoretical model proposed by Hammond et al. (2021), which comprehensively analyzes the low adoption rate of green buildings through a systematic analysis method. The study also draws on other scholars' research on the obstacles to the reuse of construction waste. For example, Pham et al. (2023) explored the impact of transformative leadership in the construction supply chain and developed a sustainable supply chain framework based on transformative leadership. Through empirical analysis, this study verified that improving stakeholder awareness and participation, as well as developing targeted policies and incentives, can significantly improve the reuse rate of building construction and demolition waste, which is consistent with the research results of Pham et al. (2023) To sum up, this study not only compares and analyzes different viewpoints on building construction and demolition waste management, but also clarifies the supporting role of circular economy theory and change management theory in this study, and verifies these theories through empirical research results. It provides theoretical basis and practical guidance for effective management of construction and demolition waste and sustainable development of construction industry.

5 Conclusion

In the development of urbanization, the reuse of abandoned buildings has a positive significance for resource conservation and sustainable development. To overcome the difficulties of reuse and optimize the existing strategies for the reuse of abandoned buildings, the material flow and obstacle analysis of abandoned building waste were carried out, aiming to further improve the resource recovery and utilization rate. The theoretical contribution of the research is that through in-depth analysis of the management practice of building construction and demolition waste, combined with the theory of circular economy, a set of systematic resource strategy model is proposed, which not only enriches the existing theoretical system of building construction and demolition waste management, but also provides a theoretical basis for realizing the efficient recycling and reuse of construction waste. On this basis, network clustering and density analysis were carried out to carry out targeted optimization strategies. The network analysis results showed that the network density reached 0.052, indicating that there was significant optimization space in the current reuse network. Further testing was conducted on the effectiveness of the optimization strategy. The test results showed that the waste recovery rate of the improved strategy reached 82.7%. Compared with the traditional scheme, the recovery rate increased rapidly, with an increase of 67.4%. In addition, the resource utilization rate increased by 50.1% compared with traditional schemes. The practical guiding significance of the research is that the resource strategy model provides specific operational framework and implementation steps for the management of construction and demolition waste, and provides clear action guidelines for the construction industry practitioners, policy makers and relevant stakeholders to help them make more effective decisions in the actual operation. It indicates that the optimization scheme has effectively promoted sustainable resource utilization. Although this strategy has achieved significant results in improving recovery rates and resource utilization, the lack of centralized network structure still needs to be further addressed. Future work will focus on optimizing the network structure, enhancing the connectivity and role of core nodes, thereby stimulating the potential of the entire recycling network and further promoting the sustainable development. Through continuous research and practice, it is expected to provide a more solid theoretical foundation and practical guidance for maximizing the utilization of abandoned building resources and sustainable urban ecological construction.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

JC: Investigation, Writing–original draft. HW: Investigation, Writing–review and editing. BS: Supervision, Writing–review and editing. WL: Investigation, Writing–original draft.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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