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Article

Evaluating Critical Barriers to Utilization of Solid Waste as Building Material (USB) in China: An Integrated DEMATEL Approach

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Abstract

Utilization of solid waste as building material (USB) is a promising strategy that effectively addresses the challenges of safety and environmental pollution posed by solid waste and alleviates the scarcity of natural resources to facilitate the sustainable production of building materials. However, USB implementation and promotion have not yet matured in China because of various barriers. Therefore, this study employed the GT-DEMATEL-ISM-MACMIC model to identify the critical factors in USB implementation and examine the interactions and relationships among barriers to propose targeted recommendations. The results identified 33 barriers and revealed a distinct causal hierarchy. It was found that the macro-level barriers at the apex of the hierarchy, 'incomplete policies and legislation', 'poor supervision and regulation of solid waste', and 'insufficient financial subsidies and incentives', are critical barriers to USB implementation. A key outcome of this study is the identification of the most critical and obstinate barrier path evolution in USB implementation, where incomplete policies and regulations (P1, P2) lead to underdeveloped markets and capital (M6, E2), as well as low stakeholder motivation (S4), which in turn, exacerbates policy inertia and traps USB development in a state of deadlock. Conversely, detail-level barriers at the technical and managerial levels, such as 'limited innovation in management models' and 'single type and limited application of renewable building material', tend to be less influential than other barriers. Therefore, USB promotion can be achieved by strengthening policies and legislation, improving policy systems, and increasing financial subsidies. The results of this study will assist China and other developing countries in identifying critical barriers to USB implementation, offer practical approaches for promoting USB implementation, and provide methodological guidance for similar studies.

Keywords: solid waste recycling; building materials; critical barriers; DEMATEL; interpretative structural modeling; grounded theory

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1. Introduction

Rapid industrialization and urbanization in China, a developing country, have generated massive amounts of solid waste [1], the growing accumulation of which causes environmental pollution and safety hazards [2]. From 2022 to 2024, an annual average of approximately 4 billion tons of bulk solid waste was generated in China [3], with the comprehensive utilization rate hovering around 60% [4]. This should be compared with some developed regions, such as the European Union, where a recycling rate of key solid waste of over 80% has been achieved [5]. This considerable gap not only highlights the disparity between Chinese solid waste recycling practices and the best international standards [5,6], but also emphasizes the urgent need to achieve circular economy targets [7]. Incompletely exploited solid waste also represents a waste of resources [8]. However, each type of solid waste has specific and complex physicochemical properties and contains multiple compounds [9], making solid waste recycling a rather challenging process [10]. Among the various options for solid waste recycling, the utilization of solid waste as building material (USB) is widely regarded as one of the most promising pathways [11–13]. This alternative can consume a diverse range of solid waste on a large scale [8], with fewer requirements for types and quality [14–16], a variety of applications, and greater market demand [17,18]. The approach also aligns seamlessly with the national strategies for green buildings [19] and zero-waste cities [20] proposed by the Chinese government. Solid waste from various industries has been demonstrated to be recyclable into green building materials [21–23] that meet quality standards using low-carbon technologies [24]. Not only can industries that generate waste benefit economically and achieve a lower carbon footprint through USB [25,26], but the construction and building material industries can also achieve sustainable production. Therefore, USB is recognized as a promising alternative [27].

Despite the recognized potential of USB, its large-scale implementation in China remains unsatisfactory and faces numerous and complex obstacles [28], compared to the growing output of solid waste [2]. The existing literature has explored these barriers from various perspectives. Some studies have tended to concentrate on barriers related to a specific types of solid waste recycling, such as construction waste [29,30] or municipal waste [31,32], or on barriers to a single technology, such as blockchain adoption in construction waste recycling [30]. Others have analyzed barriers to the broader implementation of green building materials [33,34] and sustainable buildings [35]. However, a critical review revealed several significant limitations of the existing research. First, USB is a complex and systemic issue that involves multiple industries (Figure 1). Nevertheless, the existing studies have often adopted a fragmented perspective focusing on a single type of solid waste and failed to provide a coupled framework that integrates the barriers associated with multi-source, cross-industry solid wastes such as building materials, which is the core characteristic of USB practice. Second, most studies have identified and ranked barriers but overlooked the complex, interdependent relationships and causal web among them. Finally, systematic and causal analyses of the barriers to USB implementation are particularly scarce within the unique policy, market, and technological context of China in the existing literature.

Therefore, to address these research gaps, the purpose of this study is to use an integrated DEMATEL approach for identifying the critical barriers to USB implementation in the Chinese context and investigating their interaction and causal relationship, as well as recommend effective countermeasures. The novelty of this study lies in its coupled and systematic perspective of China's USB barriers, moving beyond the single waste stream paradigm. This study also provides insights for developing countries where USB implementation is still in an embryonic stage. The remainder of this paper is organized as follows: The next section reviews the relevant theoretical foundation based on barrier identification. An integrated DEMATEL approach is explained in the following part. The results are presented in Section 4. The paper continues with a discussion (Section 5) and, finally, conclusions are presented in Section 6.

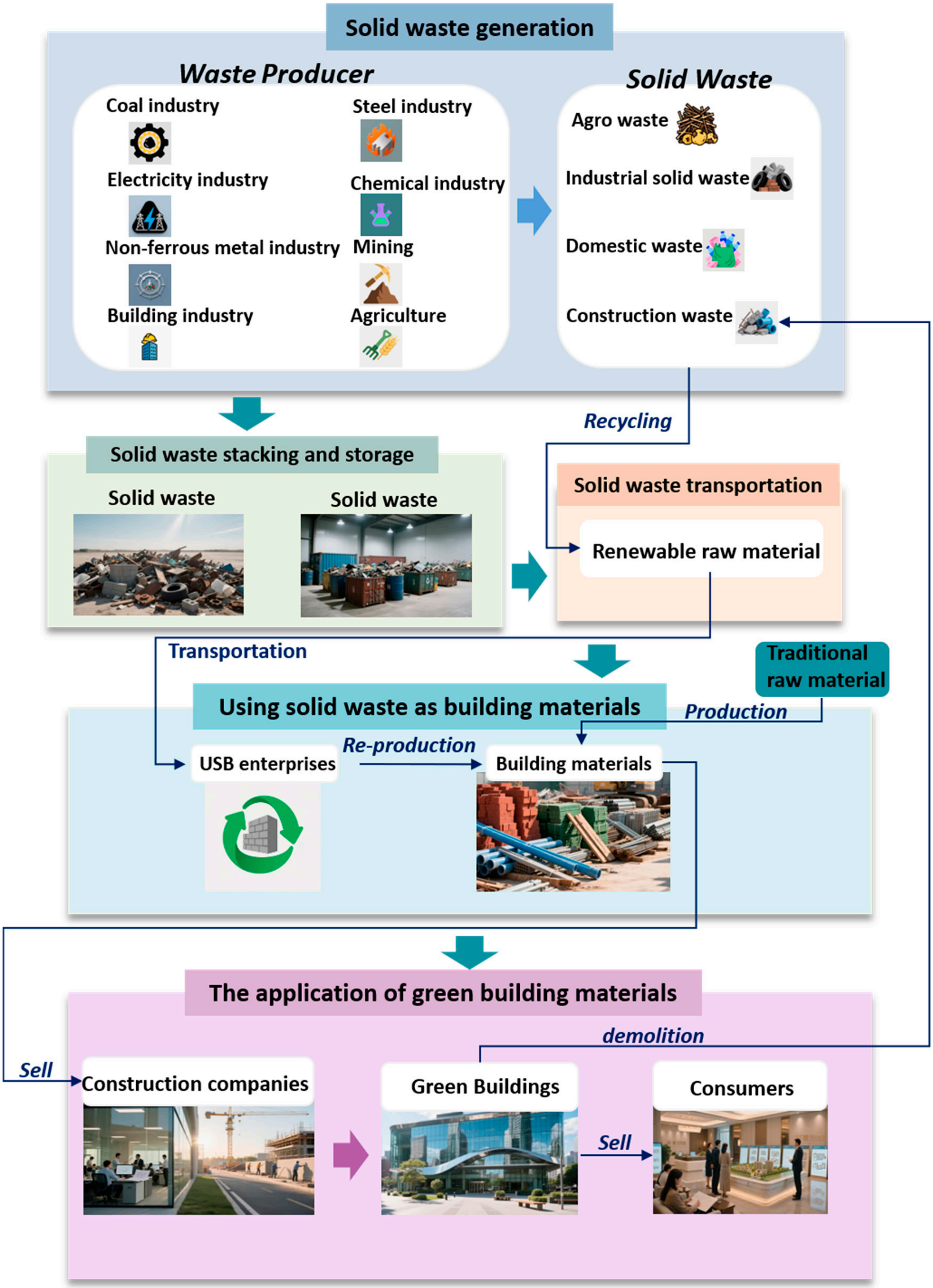

Figure 1. USB industrial chain.

2. Theoretical Foundations and Barrier Identification

Owing to the complexity of USB implementation in China, adopting multiple theories contributes to a better understanding about overcoming USB barriers. Thus, several theories within current waste management research are provided as a theoretical foundation for the validation of USB barriers in this study. USB barriers were identified using the grounded theory method, as detailed in Section 3.2.1. The theoretical foundations and USB barriers are listed in Table 1. In the following subsections, this study briefly discusses each of these theories and their suitability for application in the context of the barriers to USB implementation in China.

2.1. Stakeholder Theory (ST)

Stakeholder theory (ST) emphasizes the importance of considering the interests of all stakeholders within an organization or project [36]. In the context of China, where the government plays a dominant role and where a substantial number of informal recycling enterprises coexist with formal enterprises, ST is important for identifying conflicts of interest among different participants to achieve a balance and win-win situation for the interests of multiple stakeholders [37]. Multiple stakeholders are involved in the USB industry chain, including the government, the public, waste producers, USB enterprises, logistics enterprises, third parties, and other related enterprises. Each stakeholder has distinct motivations and concerns. This theory helps to explain barriers generated by stakeholder interactions, such as 'unclear responsibility subject', 'cost competition between informal and formal recycling enterprises', and 'lack of willingness and motivation for participation among stakeholders' (Table 1).

2.2. Institutional Theory (INT)

Institutional theory (INT) focuses on the influence of social structures and rules on individual behavior and society, attempting to understand and describe the impact of different institutions on organizations and social operations [38]. INT is applicable to the particular context of the governance model in China, which is characterized by a top-down leadership structure and policy directives. The success of USB implementation is heavily reliant on central-level policies and the uniformity of local-level enforcement. The failure of institutions can engender substantial impediments. INT provides a robust framework for understanding the barriers rooted in the institutional system to identify and deal with institutional problems [39]. Seven USB barriers confirmed by INT are detailed in Table 1.

2.3. Resource-Based Theory (RBT)

Resource-based theory (RBT) recognizes that firms can achieve a sustained competitive advantage by effectively managing and utilizing intangible and tangible resources that are unique and scarce [40]. This theory can also be applied to USB implementation under certain conditions. In the rapidly developing Chinese economy, the immense demand for resources, urgency of technological upgrading, and density of capital investment have made the capture and assignment of resources in terms of capital, technology, talent, and markets a critical constraint on USB development. Eighteen barriers recognized by RBT are detailed in Table 1.

2.4. Sustainability Science (SS)

Sustainability science (SS) aims to achieve a balance between economic development and environmental protection by exploring the interactions among human society, economic systems, and the natural environment [41]. China is currently advocating a circular economy, but sustainable development principles have not yet been fully absorbed into the construction and building material industries. This theory can help identify and address sustainability barriers to USB implementation, in order to ensure sustainability in terms of the economy, society, and environment [42]. Six barriers related to SS are detailed in Table 1.

2.5. Transaction Costs Theory (TCT)

The transaction costs theory (TCT) analyzes the various costs in market transactions, as well as the trading strategies and causes in different market environments. For the emerging USB market in China, transaction costs are particularly high. Costly transaction expenses may lead to the economic unfeasibility of USB projects, thereby hindering investment and participation of enterprises. This theory helps to understand the various cooperative and transactional behaviors involved in USB implementation, as well as to optimize these behaviors [43]. Nine barriers explained by TCT are detailed in Table 1.

2.6. Theory of Planned Behavior (TPB)

The theory of planned behavior (TPB) suggests that human behavior depends on attitudes towards behavior and perceptions of how much control there is on their behavior [44]. Massive advocacy and education activities led by the government directly shape public attitudes in China, while strong social opinions and subjective norms greatly influence individual participation in USB activities. Meanwhile, practical limitations such as access to supporting infrastructure directly impact individual behaviors. This theory can be used to better analyze and understand the behavioral intentions and behavioral choices of various stakeholders, including enterprises, government, the public, and so on. Nine barriers explained by TPB are detailed in Table 1.

2.7. Social Network Theory (SNT)

Social network theory (SNT) underlines the impact of social relationships on individual behavior and organizational structure [45], and can help with understanding the relationships and interactions between stakeholders involved in USB implementation [46]. This theory is highly relevant in the Chinese business environment, where interpersonal networks profoundly shape supply chain operations and information exchange. This unique relationship-based culture can serve as a lubricant that fosters trust and efficient cooperation, but can also result in information barriers that hinder the market-oriented information exchange of waste supply and demand. The two factors, 'limited knowledge among suppliers and demanders about recycling trading channels and the supply chain of solid waste' and 'lack of communication and cooperation between partners', are associated with SNT (Table 1).

Table 1. Critical barriers and theoretical foundations.

Barrier Category	Barriers	Code	Related Theories	References
Policy (P)	Incomplete policies and legislation	P1	INT	[47,48]
	Poor supervision and regulation of solid waste	P2	TPB, INT	[49,50]
	Unclear responsibility subject	P3	ST	[51,52]
	Insufficient publicity and education by relevant authorities	P4	TPB, RBT	[29,53]
	Lack of demonstration projects and practical experience for replication	P5	RBT, INT	[34,53]

Table 1. *Cont.*

Barrier Category	Barriers	Code	Related Theories	References
Economy (E)	Insufficient financial subsidies and incentives	E1	TCT, RBT	[29,31]
	Insufficient private capital investment by enterprises	E2	RBT	[29,52]
	High cost involved in waste disposal and recycling	E3	TCT	[29,54]
	Extra cost for transportation and storage sites of solid waste	E4	RBT, TCT	[55,56]
	High price and low profitability of green building materials	E5	SS, TCT	[57]
	Cost competition between informal and formal recycling enterprises	E6	ST	[52,56]
	Insufficient investment in technology development and innovation	E7	RBT	[34,52,55]
	Inadequate investment in equipment and infrastructure	E8	TCT, RBT	[52,56]
Society (S)	Poor consumer trust in green building materials	S1	TPB, SS	[52,55]
	Low media publicity for renewable building materials and demonstration projects	S2	RBT, TPB	[29,34]
	Limited public awareness towards environmental protection and waste recycling	S3	TPB, SS	[52,55]
	Lack of willingness and motivation for participation among stakeholders	S4	TPB, ST	[29,56]
	Insufficient awareness of circular economy and sustainable development in the AEC industry and building material industry	S5	SS	[29,49]
Technology (T)	Lack of technical and quality standards for USB	T1	INT	[49,58]
	Weak application of information technology	T2	RBT	[55]
	Single type and limited application of renewable building material	T3	RBT, SS	[59]
	Unclear composition of solid waste	T4	RBT	[52,53]
Management (M)	Insufficient training of relevant personnel	M1	RBT	[52,55]
	Limited skilled labor	M2	RBT	[49,52]
	Lack of standards and certification for USB enterprises	M3	INT, TPB	[49,52]
	Limited innovation in management models	M4	INT, TPB	[49,52]
	Unclear mechanism towards cleaner production and sustainable development of enterprises	M5	INT, TPB	[52,53]
	Undeveloped markets for comprehensive utilization and recycling of solid waste	M6	TCT, RBT	[29,34]

Table 1. *Cont.*

Barrier Category	Barriers	Code	Related Theories	References
Information (I)	Limited knowledge among suppliers and demanders about recycling trading channels and supply chain of solid waste	I1	TCT, RBT, SNT	[52,59]
	Lack of communication and cooperation between partners	I2	SNT	[29,52,55]
	Non-transparent and imperfect price information in the recycling market of solid waste	I3	RBT, TCT	[34,55]
	Lack of awareness about market value for USB among stakeholders	I4	ST, SS, RBT	[34,59]
	Lack of prediction of waste generation and recycling capacity	I5	TCT, RBT	[29,52]

3. Methodology

3.1. Research Framework

An integrated DEMATEL approach (GT-DEMATEL-ISM-MACMIC) was used in this study, which involves grounded theory (GT), decision making trial and evaluation laboratory (DEMATEL), interpretative structural modeling (ISM), and cross-impact matrix multiplication applied to classification (MICMAC). The detailed steps are as follows:

Step 1: Application of grounded theory (GT). Specifically, the GT method was first employed to analyze and code the data, thereby identifying 33 barriers affecting the implementation of USB in China.

Step 2: Implementation of the DEMATEL method. The DEMATEL method was used to construct a direct impact matrix between the barriers, analyze the complex interactions between the barriers, and calculate the relevant influence indicators, thereby identifying the critical barriers. Additionally, the cause-and-effect diagram constructed using the DEMATEL method can visualize the interactions and cause-and-effect associations among critical barriers.

Step 3: Structural analysis using ISM. Based on the above, the whole system of barriers in terms of the sequential and hierarchical structure was then analyzed by the ISM method.

Step 4: Driving-dependence analysis via MICMAC. The MICMAC method is a further extension of the ISM model for identifying the driving force and dependence degree of barriers in complex systems.

Therefore, an integrated GT-DEMATEL-ISM-MACMIC methodology applied to barrier analysis can be cross-validated from diverse perspectives to identify critical barriers more effectively and reveal the implicit interactions and relationship paths among critical barriers, thus providing a valid foundation for further developing targeted optimization strategies. Figure 2 illustrates the research framework of this study.

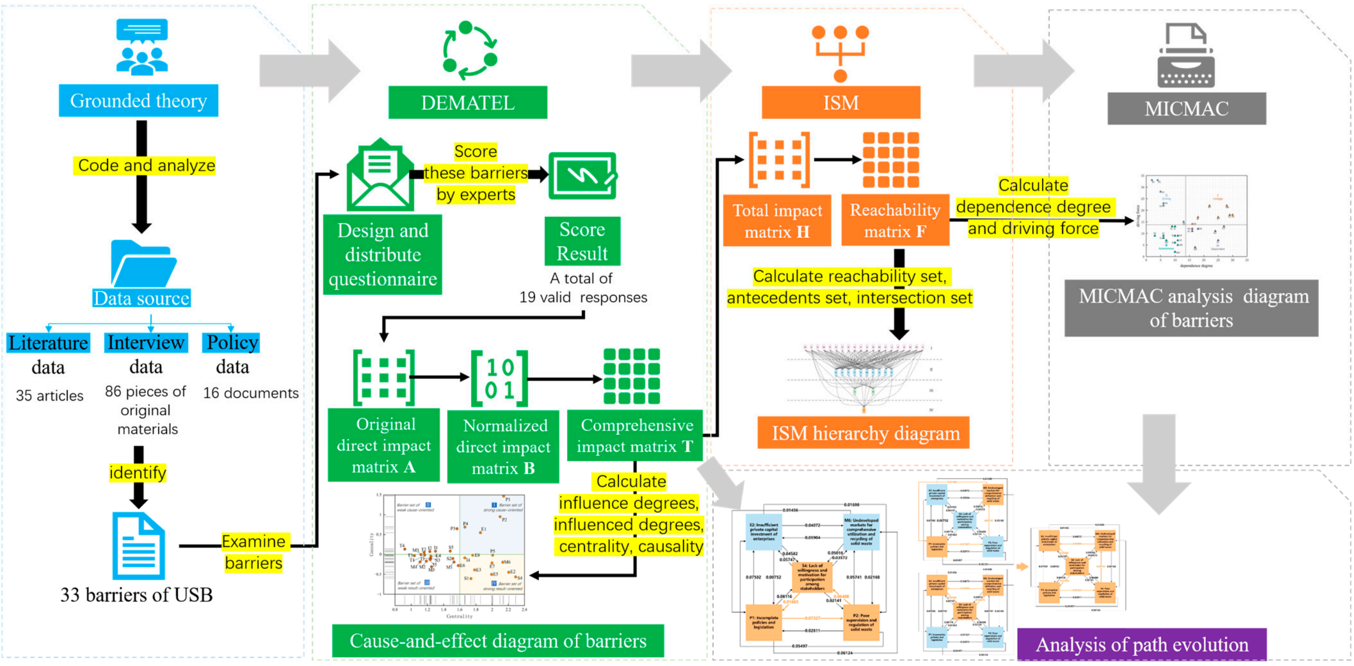

Figure 2. Steps of the proposed research framework.

3.2. Analytical Methods and Data

3.2.1. Grounded Theory Method and Data

The GT method emphasizes the systematic coding, classification, summarization, and conceptualization of the relevant information collected from actual and real experience, from which the core concepts are extracted to construct a theoretical framework [60].

Specifically, the original information required for GT is mainly derived from the literature, interviews, and policy. To ensure comprehensive coverage of publications related to the field of research, literature data for the GT method were collected from the Web of Science (WOS) Core Collection, one of the leading databases of scientific publications. The following search string was used to examine the title, abstract keywords, and topic fields: (“waste* manage*” OR “solid* waste*” OR “recycling* waste*” OR “building* material*” OR “construction* material*”) AND (“factor*” OR “barrier*” OR ′′driver*” OR “obstacle*” OR “determinant*” OR “strategy*”). A total of 135 items were obtained during the initial screening. Because almost no literature directly related to USB barriers is available, this study included in the literature pool indirect literature with research topics such as solid waste management and recycling, construction waste recycling, or building materials. After full text examination, 35 articles were retained. Among them, 25 articles were used for coding, and the remaining 10 articles were used for saturation testing. In addition, the interview data were derived from the records of interviewing practitioners within the USB industry chain, with 86 items obtained from the original interview corpus. The policy data were derived from policies on USB issued by the Chinese government between 2022 and 2024, with 16 policy documents obtained.

The coding process of grounded theory comprises three core stages: open coding, axial coding, and selective coding. This study identified six barrier categories and 33 barriers to USB (Table 1) by coding and analyzing all three types of raw data (the literature, interviews, and policies) sentence-by-sentence (Table 2) to form a questionnaire for further investigation.

Table 2. Partial open-coding results for USB barriers (as an example).

Data Source		Original Materials	Open Coding	Axial Coding	Selective Coding
Interview record	Interviewee 1	Solid waste collection and transportation involves long-distance transportation and specialized treatment, which leads to high logistics costs, directly raising the production costs of USB and, to a certain extent, restricting the economic feasibility of resource utilization.	Solid waste is more costly to store and transport due to its unique characteristics and large size.	Extra cost of transportation and storage sites of solid waste.	Economy
	Interviewee 2	At present, there is too little publicity on using solid waste as building material in China. The public has limited knowledge of solid waste recycling channels, limited knowledge of using solid waste as building material, and insufficient understanding of the benefits and responsibilities of solid waste recycling.	Insufficient media publicity on solid waste building materials, and low public understanding of and trust in solid waste building materials.	Low consumer trust in green building materials.	Society
	Interviewee 3	The management system for general industrial solid waste is still in the initial stage of development. From the source of generation, storage, and transportation to resource utilization, the whole life cycle management, is related to the environment sector's regulatory responsibilities, the development and reform of industrial policy guidance, and industry standards in the industry and information technology sectors. Multi-departmental collaborative management is necessary, but at present, each department's boundaries and division of powers and responsibilities is not clear enough, which to a certain extent, restricts the standardized development of general industrial solid waste in the field of building material utilization.	Incomplete policies and legislation. The solid waste management system does not yet have an established a set of systematic processes, and the division of authority and responsibility among multiple departments is not yet clear.	Poor supervision and regulation of solid waste.	Policy
		……			
Literature	Investigating Barriers to Sustainable Management of Construction and Demolition Waste: the Case of India [61]	At present, the field of solid waste management is facing the problem of insufficient trained professional personnel. Specifically, this manifests as follows: practitioners generally lack systematic solid waste management knowledge training and professional skills training. This lack of professionalism not only increases the risk of errors in the operation process but also directly affects the overall efficiency of the utilization of solid waste building material.	Inexperience and inefficiency of some staff in the solid waste area.	Insufficient training of relevant personnel and limited skilled labor.	Management

Table 2. *Cont.*

	Data Source	Original Materials	Open Coding	Axial Coding	Selective Coding
	Analysis of Factors Affecting the Circularity of Building Materials [34]	The current solid waste-based building material market still comprises low-quality construction materials with low recycling potential, and is based on low-cost technologies.	Current markets for integrated solid waste utilization and recycling are underdeveloped.	Undeveloped markets for comprehensive utilization and recycling of solid waste.	Management
	Exploring the restrictive factors for the development of the construction waste recycling industry in a second-tier Chinese city: a case study from Jinan [62]	There is a lack of mature technical specifications and quality standards for recycled products, and inadequate tracking of long-term performance of recycled products.	Currently, there is a lack of technical specifications and product quality standards for waste building materials.	Lack of technical and quality standards for USB.	Technology
		……			
Policy	Guiding Opinions on Accelerating the Establishment of a Waste Recycling System	The main responsibility of waste recycling and technology paths should be clarified according to the characteristics of various types of waste, such as source, scale, resource value, utilization mode, ecological and environmental impact, etc. The resource recycling industry should be organized according to the local conditions, and the operation efficiency of the waste recycling system should be improved.	Solid waste has a complex composition with many classification criteria. It is difficult to clarify the composition, so it is not well classified and utilized.	Unclear composition of solid waste.	Technology
	Guiding Opinions on Accelerating the Comprehensive Green Transition of Economic and Social Development	Vigorously promote the green and low-carbon transformation of iron and steel, non-ferrous metals, petrochemicals, chemicals, building materials, paper, printing, and dyeing industries; promote energy-saving, low-carbon, and cleaner production technology and equipment; promote the updating and upgrading of processes.	At present, solid waste recycling enterprises generally lack clean production mechanisms and sustainable development systems for the use of building materials, especially in the pre-treatment of raw materials, recycled aggregate processing, and other key aspects. This failure to establish standardized, low-carbon operating norms restricts the efficiency of the transformation of solid waste resources into high-quality building materials.	Unclear mechanisms to achieve cleaner production and sustainable development of enterprises.	Management
		……			

3.2.2. DEMATEL Method and Data

Empirical data used for the DEMATEL method in this study were collected by means of a questionnaire survey. Initially, the barriers constructed by the GT method were examined by three invited experts, and the questionnaire was designed based on the revised barriers. The rating scale in the questionnaire was based on a Likert scale. The questionnaire was distributed to experts in relevant fields who scored the barriers according to the impact of barriers on each other. The questionnaire was distributed through an online questionnaire survey platform. The snowball sampling method [29] was adopted to contact the target experts. During this process, some respondents assisted in sending the received questionnaire links to other potential respondents, such as their colleagues or friends. A total of 19 responses were received, of which 6 were potentially invalid. Among the invalid responses, one respondent had much less experience and an unsuitable occupation, and the other five respondents completed the questionnaire in a very short time. Therefore, the invalid responses were not considered in this study. All the experts had more than five years of work or research experience related to USB. Of the thirteen respondents, six were from academia, four were from industry, and three were from government organizations. The small sample size of respondents is acceptable for this method. A sample expert panel consisting of 10 to 15 respondents is in accordance with the relevant research [29,52,63,64], and can effectively achieve the required consistency and accuracy. Table 3 presents the detailed profiles of the experts.

Table 3. Detailed profile of experts.

Expert	Education	Experience	Affiliations	Professional Title
Expert 1	PhD	12	Research institution	Professor
Expert 2	PhD	5	Research institution	Research fellow
Expert 3	PhD	7	Research institution	Associate research fellow
Expert 4	PhD	8	Research institution	Associate research fellow
Expert 5	PhD	15	University	Professor
Expert 6	PhD	12	University	Professor
Expert 7	PhD	7	University	Associate professor
Expert 8	PhD	8	University	Associate professor
Expert 9	PhD	8	Governmental agencies	Government executive
Expert 10	Master	11	Governmental agencies	Public servant
Expert 11	Master	9	Building material enterprise	Manager
Expert 12	Master	13	Building material enterprise	Manager
Expert 13	Master	8	Construction contractor	Project manager

Based on the score results obtained from the questionnaire, the original direct impact matrix A was obtained, and then the original direct impact matrix was normalized (1) to obtain the normalized direct impact matrix B. The comprehensive impact matrix T was then calculated (2) based on the normalized direct impact matrix B. Furthermore, the influence degree, influenced degree, centrality, and causality of each barrier were calculated from the comprehensive impact matrix T. The influence degree C is the sum of the rows in matrix T, indicating the overall impact of each row of barriers on all other barriers. The influenced degree E is the sum of the columns in the matrix T, indicating the overall impact of each column of barriers on all other barriers. The centrality C+E represents the summed value of the influence degree and the influenced degree, indicating the importance of the barriers in the system. The causality C-E represents the value of the influence degree with the influenced degree subtracted. Finally, a cause-and-effect diagram of barriers was drawn with centrality as the horizontal coordinate and causality as the vertical coordinate.

$$M = Min\left[\frac{1}{Max\sum_{j=1}^{n} aij}, \frac{1}{Max\sum_{i=1}^{n} aij}\right]$$

$$B = M \times A \tag{1}$$

$$T = B(I - B)^{-1} \tag{2}$$

3.2.3. ISM Method

The hierarchical relationship between the various USB barriers interacting at different levels was interpreted using the ISM method based on the cause-and-effect results. This work involves the following steps.

First, calculate the reachability matrix F. Set the number less than the threshold λ in the matrix H to 0 and the others to 1 to obtain the reachability matrix F (3). The total impact matrix is H = T + I, where T is the comprehensive impact matrix, and I is the unit matrix. Specifically, calculate the average α and standard deviation β of the total impact matrix H to obtain the threshold λ, which is the sum of the average α and standard deviation β.

Then, calculate the reachability set (4), antecedent set c, and intersection set (Equation (6)). The reachability set is the barriers corresponding to the column with value 1 in each row, indicating the set of the barrier itself, and all other barriers that it holds influence over [30]. The antecedent set is the barriers corresponding to the column with a value of 1 in each column, indicating the set of the barrier itself and all other barriers that exert influence on it [63].

$$f_{ij} = \begin{cases} 1, e_{ij} \geq \lambda(\mathrm{i}, \mathrm{j} = 1, 2, \ldots, \mathrm{n}) \\ 0, e_{ij} < \lambda(\mathrm{i}, \mathrm{j} = 1, 2, \ldots, \mathrm{n}) \end{cases} \tag{3}$$

$$Ri = \{fi|Fij = 1\} \tag{4}$$

$$Si = \{fi|Fij = 1\} \tag{5}$$

$$Ri \cap Si \tag{6}$$

Finally, perform a few iterations of interval partition and level partition for the barriers. Specifically, the barriers in Ri are identified as the highest level when Ri = Ri∩Si is satisfied. Remove the partitioned barriers from Ri, Si, and the intersection set, and follow this procedure to continually iterate to find the next level and thus form the final hierarchical relationship. A higher level indicates a stronger influence but less dependence.

3.2.4. MICMAC Method

The MICMAC method is employed to calculate the driving force and dependence degree for each barrier based on the reachability matrix F and categorizes the barriers, thus revealing the overall structure of the system and the interaction of the factors in it. After the values of the driving force D and dependence degree R are calculated using Equations (7) and (8). The barriers are categorized into 4 groups, and a classification diagram of barriers is drawn.

$$Di = \sum_{j=1}^{n} a_{ij}^{F} \tag{7}$$

where a_{ij}^{F} is the element of the row i and column j of F, and Di is the sum of row i of F.

$$Rj = \sum_{i=1}^{n} a_{ij}^{F} \tag{8}$$

Rj is the sum of column j of F.

4. Results

Based on the analytical methods and data outlined in the previous section, the results of the GT-DEMATEL-ISM-MACMIC model are presented below.

4.1. DEMATEL Results

A comprehensive impact matrix T was obtained using the DEMATEL method, which provided a calculated value of the influence degree, influenced degree, centrality, and causality of each barrier (Table 4). The value of centrality reflects how important a barrier is to the whole USB barrier system, and the higher the centrality, the more important the barrier and the greater the impact on the system. A positive value of centrality corresponds to a cause-oriented barrier, which indicates that the barrier tends to influence other barriers, thus directly affecting USB implementation. A negative value of centrality corresponds to a result-oriented barrier, which indicates that the barrier is more influenced by other barriers, thus indirectly affecting USB implementation. Figure 3 shows the cause-and-effect diagram based on the DEMATEL method, which categorizes barriers into four groups and locates them in each of the four quadrants according to the values of centrality and causality. The X-axis indicates centrality, and the Y-axis represents causality in Figure 3.

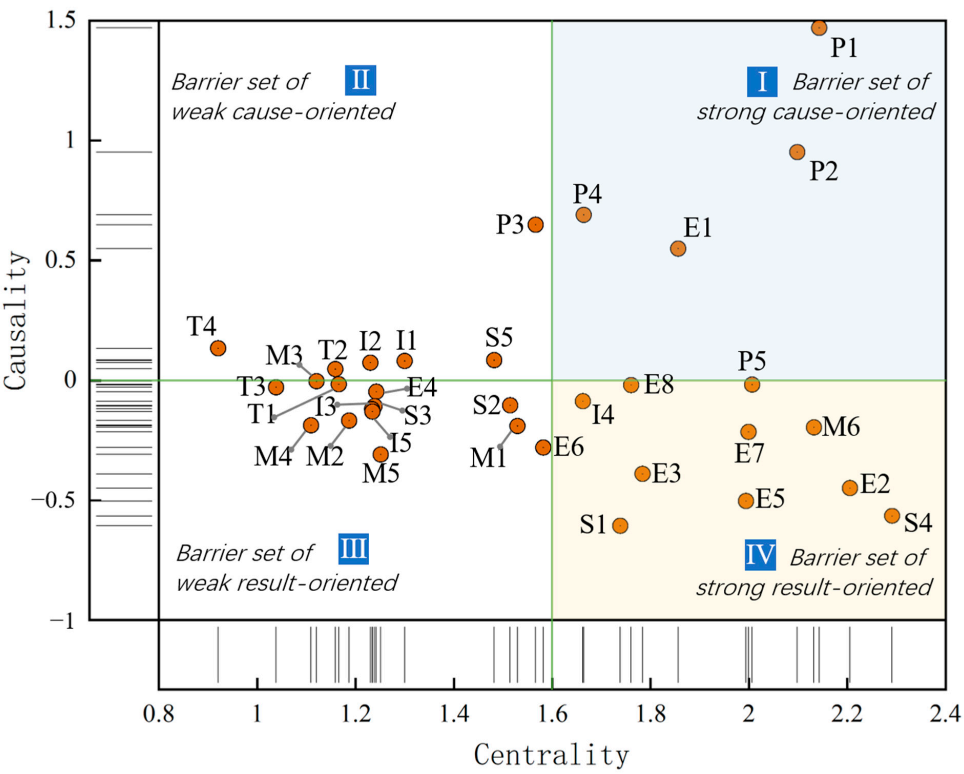

Figure 3. Cause-and-effect diagram of barriers.

Table 4. Ranking of centrality and causality.

Barriers	Influence Degrees	Influenced Degrees	Centrality	Ranking of Centrality	Causality	Ranking of Causality
P1	1.80677	0.33627	2.14304	3	1.4705	1
P2	1.52518	0.57311	2.09829	5	0.95207	2
P3	1.10789	0.45826	1.56615	16	0.64963	4
P4	1.17716	0.4869	1.66406	13	0.69026	3
P5	0.99452	1.01191	2.00643	6	−0.01739	13
E1	1.20276	0.65328	1.85604	9	0.54948	5
E2	0.87827	1.32711	2.20538	2	−0.44884	30
E3	0.69695	1.08656	1.78351	10	−0.38961	29
E4	0.5978	0.64448	1.24228	22	−0.04668	16
E5	0.74565	1.24835	1.994	8	−0.5027	31
E6	0.65123	0.93076	1.58199	15	−0.27953	27
E7	0.8924	1.10677	1.99917	7	−0.21437	26
E8	0.8705	0.88994	1.76044	11	−0.01944	14
S1	0.56515	1.17311	1.73826	12	−0.60796	33
S2	0.70558	0.80891	1.51449	18	−0.10333	18
S3	0.56611	0.67276	1.23887	23	−0.10665	19
S4	0.86281	1.42826	2.29107	1	−0.56545	32
S5	0.78329	0.6986	1.48189	19	0.08469	7
T1	0.57525	0.59079	1.16604	28	−0.01554	12
T2	0.60316	0.5558	1.15896	29	0.04736	10
T3	0.50478	0.53353	1.03831	32	−0.02875	15
T4	0.52732	0.39335	0.92067	33	0.13397	6
M1	0.66979	0.85944	1.52923	17	−0.18965	24
M2	0.5101	0.67693	1.18703	27	−0.16683	22
M3	0.55883	0.56191	1.12074	30	−0.00308	11
M4	0.46127	0.64826	1.10953	31	−0.18699	23
M5	0.47126	0.78005	1.25131	21	−0.30879	28
M6	0.96832	1.16396	2.13228	4	−0.19564	25
I1	0.69061	0.60936	1.29997	20	0.08125	8
I2	0.6522	0.57803	1.23023	26	0.07417	9
I3	0.55688	0.67689	1.23377	25	−0.12001	20
I4	0.78786	0.87464	1.6625	14	−0.08678	17
I5	0.55252	0.68189	1.23441	24	−0.12937	21

Based on the results of DEMATEL, T4 (unclear composition of solid waste) and S1 (low consumer trust in green building materials) have the lowest centrality and causality degrees among the barriers. S4 (lack of willingness and motivation for participation among stakeholders) and P1 (incomplete policies and legislation) have the highest centrality degree and causality degree among the barriers. In addition, P1 (incomplete policies and legislation), P2 (poor supervision and regulation of solid waste), and E1 (insufficient financial subsidies and incentives) are the top three barriers with the highest sum of centrality and causality degrees, as well as M4 (limited innovation in management models), M5 (unclear mechanism towards cleaner production and sustainable development of enterprises), and T3 (single type and limited application of renewable building material) are the top three barriers with the lowest sum of centrality and causality degrees. It can be inferred that policies and legislation are vital to USB implementation, while technology details and demand-side barriers have less influence on USB implementation at the current development stage compared with other barriers. Meanwhile, it is important to enhance the willingness and motivation for participation among stakeholders.

The path evolution of critical barriers to USB implementation can reveal the dynamic impact system formed by different interaction patterns and feedback mechanisms between critical barriers. According to the comprehensive impact matrix T, five critical barriers, P1, P2, E2, S4, and M6, were selected to build the comprehensive impact matrix T′5 × 5 of the critical barriers (Table 5), based on which the path evolution diagram (Figure 4) and the composite path evolution diagram of the critical barriers (Figure 5) were drawn. In Figures 4 and 5, the numbers on the arrow indicate the magnitude of influence, and any three barriers interact to form a closed loop. In this study, the loop formed by the three barriers was defined as the base path, and the path formed by the interaction between the base path and other barriers was called the composite path. The sums of the 20 composite paths are shown in Figures 4 and 5.

Table 5. Comprehensive impact matrix of USB critical barriers in China.

Barrier	P1	P2	E2	S4	M6
P1	1.01089	0.07327	0.07592	0.08116	0.06124
P2	0.02811	1.01534	0.05497	0.06408	0.05741
E2	0.00752	0.01698	1.0207	0.04582	0.04072
S4	0.01663	0.02141	0.05747	1.0221	0.03572
M6	0.01456	0.02168	0.05904	0.05016	1.02016

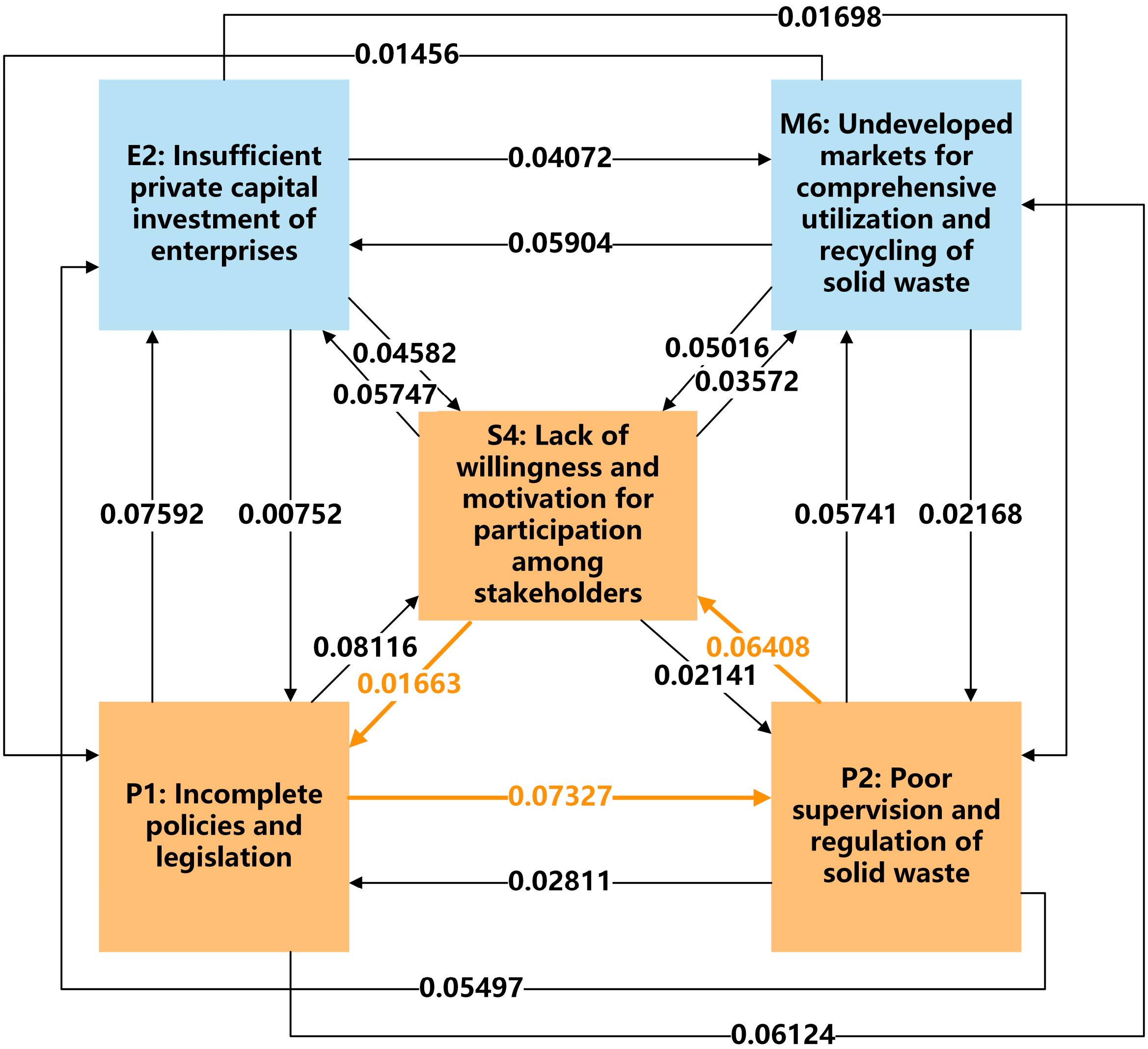

Figure 4. Path evolution of USB critical barriers in China.

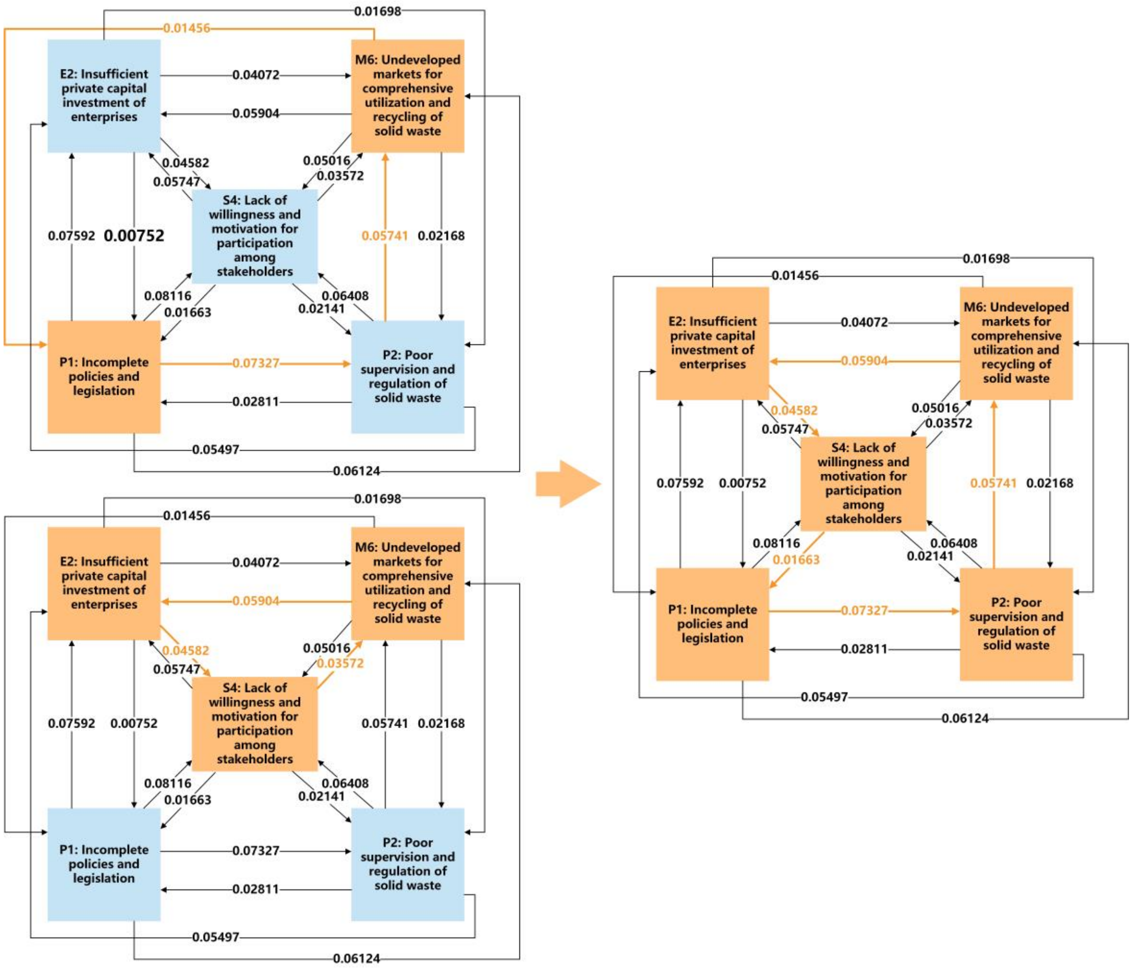

Figure 5. Evolution diagram of composite path.

The base path with the largest weight in Figure 3 is P1→P2→S4→P1 (0.15398), and the composite path with the largest weight is P1→P2→M6→E2→S4→P1 (0.25217). The weight of the composite path is higher than that of the base path, indicating that the difficulty of USB implementation in China increases with the complexity of the interactions.

After coupling the two base paths P1→P2→M6→P1 (0.14524) and M6→E2→S4→M6 (0.14058), the composite path P1→P2→M6→E2→S4→P1 (0.25217) was obtained, as shown in Figure 4. This indicates a vicious cycle whereby the incomplete policies and legislation (P1) exacerbate the poor supervision and regulation of solid waste (P2), which further leads to undeveloped markets for comprehensive utilization and recycling of solid waste (M6), thus resulting in insufficient private capital investment of enterprises (E2), and ultimately causing lack of willingness and motivation for participation among stakeholders (S4), which in turn aggravates P1.

4.2. ISM Results

The hierarchical relationships of the 33 barrier factors in this study were determined over four iterations, as shown in Figure 6. The top layer (I) of barriers is the apparent cause, the middle two layers of barriers are indirect causes, and the bottom layer (IV) is the underlying cause. Table 6 shows the results of all iterations.

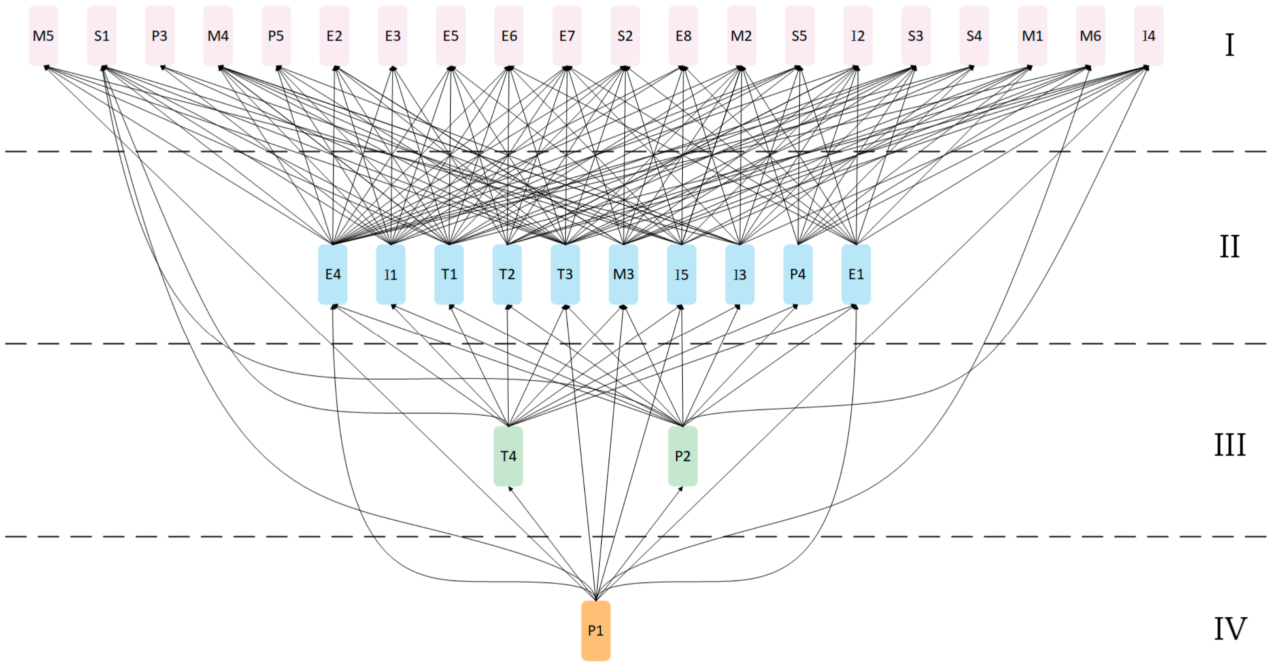

Figure 6. ISM hierarchical relations diagram of barriers.

Table 6. Results of four iterations of barriers.

Barriers	Reachability Set	Antecedents Set	Intersection Set	Level
P1	P1, P2, P3, P4, P5, E1, E2, E3, E4, E5, E6, E7, E8, S1, S2, S3, S4, S5, T1, T2, T3, T4, M1, M2, M3, M4, M5, M6, I1, I2, I3, I4, I5	P1, P2	P1, P2	IV
P2	P1, P2, P3, P4, P5, E1, E2, E3, E4, E5, E6, E7, E8, S1, S2, S3, S4, S5, T1, T2, T3, T4, M1, M2, M3, M4, M5, M6, I1, I2, I3, I4, I5	P1, P2, P3, E1	P1, P2, P3, E1	III
P3	P2, P3, P4, P5, E1, E2, E3, E4, E5, E6, E7, E8, S1, S2, S3, S4, S5, T1, M1, M2, M3, M4, M5, M6, I1, I2, I4, I5	P1, P2, P3, S4, M1	P2, P3, S4, M1	I
P4	P4, P5, E2, E3, E5, E7, E8, S1, S2, S3, S4, S5, T2, M1, M2, M3, M4, M5, M6, I1, I3, I4, I5	P1, P2, P3, P4, E1, I4	P4, I4	II
P5	P5, E2, E3, E5, E7, E8, S1, S2, S3, S4, S5, T1, M1, M2, M3, M4, M5, M6, I1, I3, I4, I5	P1, P2, P3, P4, P5, P6, P7, E3, E5, E7, E8, S2, S4, S5, T1, T2, T3, M1, M3, M6, I2, I4	P5, E1, E2, E5, E7, E8, S2, S4, S5, T1, M1, M3, M6, I4	I
E1	P2, P4, P5, E1, E2, E3, E4, E5, E6, E7, E8, S1, S2, S3, S4, S5, M1, M2, M4, M5, M6, I4	P1, P2, P3, E1, M6, I4	P2, E1, M6, I4	II

Table 6. *Cont.*

Barriers	Reachability Set	Antecedents Set	Intersection Set	Level
E2	P5, E2, E3, E4, E5, E6, E7, E8, S1, S2, S4, S5, T2, M1, M2, M5, M6, I4	P1, P2, P3, P4, P5, E1, E2, E3, E4, E5, E6, E7, E8, S1, S2, S3, S4, S5, T1, T2, T3, M1, M3, M6, I1, I2, I3, I4, I5	P5, E2, E3, E4, E5, E6, E7, E8, S1, S2, S4, S5, T2, M1, M6, I4	I
E3	P5, E2, E3, E4, E5, E6, E7, E8, S4, M5, M6	P1, P2, P3, P4, P5, E1, E2, E3, E4, E5, E6, E7, E8, S1, S2, S4, S5, T4, M2, M6, I1, I2, I3, I4	P5, E2, E3, E4, E5, E6, E7, E8, S4, M6	I
E4	E2, E3, E4, E5, E6, E7, E8, S4, M6	P1, P2, P3, E1, E2, E3, E4, E6, E7, E8, T4	E2, E3, E4, E6, E7, E8	II
E5	P5, E2, E3, E5, E6, E7, E8, S1, S4, M1, M5, M6, I4	P1, P2, P3, P4, P5, E1, E2, E3, E4, E5, E6, E7, E8, S1, S2, S4, S5, T3, T4, M1, M2, M5, M6, I1, I2, I3, I4	P5, E2, E3, E5, E6, E7, E8, S1, S4, M1, M5, M6, I4	I
E6	E2, E3, E4, E5, E6, E7, S4, M5, M6, I1, I2, I3	P1, P2, P3, E1, E2, E3, E4, E5, E6, E7, E8, S4, S5, T1, M6, I1, I3, I4	E2, E3, E4, E5, E6, E7, S4, M6, I1, I3	I
E7	P5, E2, E3, E4, E5, E6, E7, E8, S1, S2, S4, T2, T3, M1, M4, M5, M6	P1, P2, P3, P4, P5, E1, E2, E3, E4, E5, E6, E7, E8, S4, S5, T1, T2, T3, T4, M1, M3, M5, M6, I2, I4	P5, E2, E3, E4, E5, E6, E7, E8, S4, T2, T3, M1, M5, M6	I
E8	P5, E2, E3, E4, E5, E6, E7, E8, S1, S2, S4, T3, M1, M6	P1, P2, P3, P4, P5, E1, E2, E3, E4, E5, E7, E8, S4, S5, M6, I4	P5, E2, E3, E4, E5, E7, E8, S4, M6	I
S1	E2, E3, E5, S1, S3, S4, M6	P1, P2, P3, P4, P5, E1, E2, E5, E7, E8, S1, S2, S3, S4, S5, T1, T3, T4, M1, M3, M6, I1, I2, I3, I4	E2, E5, S1, S3, S4, M6	I
S2	P5, E2, E3, E5, S1, S2, S3, S4, S5, M6, I4	P1, P2, P3, P4, P5, E1, E2, E7, E8, S2, S3, S4, S5, M6, I1, I4	P5, E2, S2, S3, S4, S5, M6, I4	I
S3	E2, S1, S2, S3, S4, S5, M6	P1, P2, P3, P4, P5, E1, S1, S2, S3, S4, I4	S1, S2, S3, S4	I
S4	P3, P5, E2, E3, E5, E6, E7, E8, S1, S2, S3, S4, S5, M1, M2, M6, I2, I4	P1, P2, P3, P4, P5, E1, E2, E3, E4, E5, E6, E7, E8, S1, S2, S3, S4, S5, T1, T3, T4, M1, M2, M3, M6, I1, I2, I3, I4, I5	P3, P5, E2, E3, E5, E6, E7, E8, S1, S2, S3, S4, S5, M1, M2, M6, I2, I4	I
S5	P5, E2, E3, E5, E6, E7, E8, S1, S2, S4, S5, M1, M5, M6, I4	P1, P2, P3, P4, P5, E1, S2, S3, S4, S5, M6, I4	P5, E2, S2, S4, S5, M6, I4	I
T1	P5, E2, E6, E7, S1, S4, T1, M6	P1, P2, P3, P5, T1, T4	P5, T1	II

Table 6. *Cont.*

Barriers	Reachability Set	Antecedents Set	Intersection Set	Level
T2	P5, E2, E7, T2, I1, I2, I3, I4, I5	P1, P2, P4, E2, E7, T2	E2, E7, T2	II
T3	P5, E2, E5, E7, S1, S4, T3, M6	P1, P2, E7, E8, T3, T4	E7, T3	II
T4	E3, E4, E5, E7, S1, S4, T1, T3, T4	P1, P2, T4	T4	III
M1	P3, P5, E2, E5, E7, S1, S4, M1, M2, M4, M5, M6	P1, P2, P3, P4, P5, E1, E2, E5, E7, E8, S4, S5, M1, M2, M6, I4	P3, P5, E2, E5, E7, S4, M1, M2, M6	I
M2	E3, E5, S4, M1, M2	P1, P2, P3, P4, P5, E1, E2, S4, M1, M2, M6	S4, M1, M2	I
M3	P5, E2, E7, S1, S4, M3, M6	P1, P2, P3, P4, P5, M3, M6	P5, M3, M6	II
M4	M4, M5	P1, P2, P3, P4, P5, E1, E7, M1, M4, M5	M4, M5	I
M5	E5, E7, M4, M5	P1, P2, P3, P4, P5, E1, E2, E3, E5, E6, E7, S5, M1, M4, M5, M6, I5	E5, E7, M4, M5	I
M6	P5, E1, E2, E3, E5, E6, E7, E8, S1, S2, S4, S5, M1, M2, M3, M5, M6, I1, I2, I3, I4, I5	P1, P2, P3, P4, P5, E1, E2, E3, E4, E5, E6, E7, E8, S1, S2, S3, S4, S5, T1, T3, M1, M3, M6, I1, I2, I3, I4, I5	P5, E1, E2, E3, E5, E6, E7, E8, S1, S2, S4, S5, M1, M3, M6, I1, I2, I3, I4, I5	I
I1	E2, E3, E5, E6, S1, S2, S4, M6, I1, I2, I3, I4, I5	P1, P2, P3, P4, P5, E6, T2, M6, I1, I2	E6, M6, I1, I2	II
I2	P5, E2, E3, E5, E7, S1, S4, M6, I1, I2, I3, I4, I5	P1, P2, P3, E6, S4, T2, M6, I1, I2	S4, M6, I1, I2	I
I3	E2, E3, E5, E6, S1, S4, M6, I3, I4	P1, P2, P4, P5, E6, T2, M6, I1, I2, I3	E6, M6, I3	II
I4	P4, P5, E1, E2, E3, E5, E6, E7, E8, S1, S2, S3, S4, S5, M1, M6, I4	P1, P2, P3, P4, P5, E1, E2, E5, S2, S4, S5, T2, M6, I1, I2, I3, I4, I5	P4, P5, E1, E2, E5, S2, S4, S5, M6, I4	I
I5	E2, S4, M5, M6, I4, I5	P1, P2, P3, P4, P5, T2, M6, I1, I2, I5	M6, I5	II

4.3. MICMAC Results

The values of the driving force and dependence degree of each barrier were further calculated based on the results of the reachability matrix, and an MICMAC analysis diagram of the barriers was drawn (Figure 7). Figure 7 takes the mean value of the driving force and dependence degree as a segmentation line, and then categorizes each of the barriers into each of these four quadrants as follows: linkage (quadrant I), driving (quadrant II), autonomous (quadrant III), and dependent (quadrant IV). In Figure 6, the X-axis indicates the dependence degree, and the Y-axis indicates the driving force. The driving force reflects the ability of each barrier to influence other barriers, whereas the dependence degree reflects the extent to which the barrier is affected by other barriers. Autonomous barriers indicate a low driving force and dependence degree; dependent barriers indicate a high dependence degree but a low driving force; linkage barriers indicate a high driving force and dependence degree; and driving barriers indicate a high driving force but a low dependence degree.

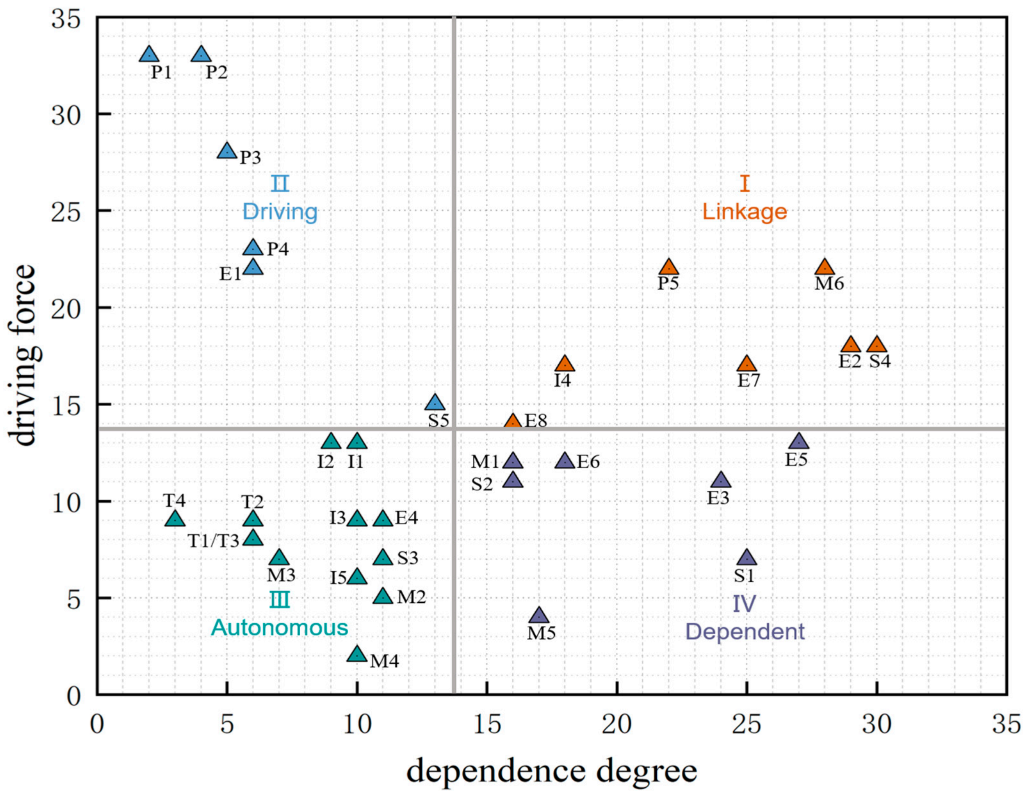

Figure 7. MICMAC analysis of barriers.

Concerning the results of the ISM and MICMAC analyses, P1 (incomplete policies and legislation), P2 (poor supervision and regulation of solid waste), P3 (unclear responsibility subject), P4 (insufficient publicity and education by relevant authorities), and E1 (insufficient financial subsidies and incentives) are the driving barriers that have the most influence on other barriers. Furthermore, M4 (limited innovation in management models), T4 (unclear composition of solid waste), M3 (lack of standards and certification for USB enterprises), T1 (lack of technical and quality standards for USB), and T3 (single type and limited application of renewable building material) are the autonomous barriers that have the lowest influence on other barriers. These results indicate that the conflicts in USB implementation focus not on technology details or management modes, but on policy regimes and economic incentives. According to the analysis of factor priority levels, P1 (incomplete policies and legislation) in level IV, P2 (poor supervision and regulation of solid waste) and T4 (unclear composition of solid waste) in level III are the most influential barriers identified due to their higher hierarchical levels compared with other barriers.

5. Discussion

A summary and comparison of the results of DEMATELHE, ISM, and MICMAC indicates that P1 (incomplete policies and legislation), P2 (poor supervision and regulation of solid waste), and E1 (insufficient financial subsidies and incentives) are the most critical barriers. In contrast, M4 (limited innovation in management models) and T3 (single type and limited application of renewable building material) are the least critical barriers compared with others. This analysis indicates that macro measures of policy systems and economic incentives can be more effective in USB implementation than detailed initiatives in society, technology, management, and information, which is attributable to the early developmental stage. This structural characteristic is indicative of the current development stage of USB in China, typifying a policy-driven emerging field.

Specifically, P1 (incomplete policies and legislation) emerges as the most fundamental barrier because, within the Chinese context, design at the top level of government is a prerequisite for market operation and regulation. P2 (poor supervision and regulation of solid waste) and M6 (undeveloped markets for comprehensive utilization and recycling of solid waste) prevent the entire industrial chain from forming stable development expectations. Similarly, M6 (undeveloped markets for comprehensive utilization and recycling of solid waste) and E2 (insufficient private capital investment of enterprises) directly weaken the intrinsic motivation for enterprise participation (S4). When enterprises are unable to guarantee economic returns or circumvent penalties for non-compliance through USB practices, a natural consequence is a lack of willingness to invest in technological research and development (T3) and management innovation (M4). Consequently, the observation that technical and managerial barriers exert less influence does not necessarily signify their irrelevance. Instead, it indicates that these barriers have not yet emerged as the predominant impediment at this stage, pending the effective resolution of the pivotal barriers of policy and market. Moreover, the most critical and obstinate barrier path evolution in USB implementation was identified in this study. Particularly, the composite path with the largest weight is 'incomplete policies and legislation (P1)'→'poor supervision and regulation of solid waste (P2)'→'undeveloped markets for comprehensive utilization and recycling of solid waste (M6)'→'insufficient private capital investment of enterprises (E2)'→'lack of willingness and motivation for participation among stakeholders (S4)'→'incomplete policies and legislation (P1)', revealing a negative cycle of USB implementation.

The findings of this study resonate with the existing international literature while also offering unique insights. Consistent with the research by Rossi et al. (2024) in Brazil and the assessment of the circular economy by Bilal et al. (2020) [65,66], our results confirm that institutions and economic incentives are the basis for advancing the waste recycling industry globally. This indicates that powerful government intervention is essential for overcoming market failures and promoting sustainable practices in any economy. While previous studies (e.g., Campbell-Johnston et al., 2019) have highlighted the importance of stakeholders [67], our study further reveals that the lack of stakeholder motivation (S4) is rooted in upstream policy and economic barriers, thus providing novel empirical evidence on the complex interactions within the USB system. This finding was confirmed by the DEMATEL analysis of path evolution in this study.

6. Conclusions

USB is essential for promoting the sustainable development of the building material and construction industries, and no studies have previously examined the critical barriers affecting USB implementation in the context of China. To fill this gap in the literature, this study employs the GT-DEMATEL-ISM-MACMIC model to identify the critical factors of USB implementation and to examine the interaction and relationships among the barriers, with the aim of proposing targeted recommendations. The main findings of this study are as follows:

(1) The grounded theory results identified 33 barriers to USB implementation, which were mainly distributed in six dimensions: policy, economy, society, management, technology, and information.

(2) The promotion of USB is not merely constrained by isolated technical or managerial issues, but is fundamentally trapped in a self-reinforcing negative cycle originating from top-level policy and economic deficiencies. The more specific conclusion is that macro-level barriers, particularly 'incomplete policies and legislation' (P1), 'poor supervision

and regulation of solid waste' (P2), and 'insufficient financial subsidies and incentives' (E1), act as the fundamental drivers of the entire barrier system. They collectively cause and aggravate a series of downstream problems, such as underdeveloped markets (M6), diminished corporate investment (E2), and a lack of stakeholder motivation (S4), ultimately creating a persistent closed loop that impedes USB development.

Given the above findings, the recommendations to strengthen USB implementation are as follows: Considering that the current USB implementation in China is still in the embryonic development stage, the government is the most important stakeholder and driving force in the USB industry chain at this stage. Therefore, a government-oriented policy system and economic incentives on the supply side are essential for USB implementation and promotion. In summary, the government should strengthen its policies and legislation, improve its policy system, and increase financial subsidies.

In general, this study adds empirical evidence to the research on USB and identifies the critical barriers and their mutual relations. These findings provide practical guidance for USB implementation and promotion in developing countries with similar challenges to China. Moreover, this study demonstrates that the integrated DEMATEL approach is a powerful tool for analyzing complex barriers and supporting policymakers and stakeholders in the USB chain in making scientific decisions, thus contributing methodologically to the field of solid waste and building material management. Nonetheless, this study has some limitations. For example, biased judgment by experts, as well as their inconsistent levels of experience and education, may result in inaccurate assessments. The error level is also increased by the randomness of the samples and insufficient response time. Future research could employ a new fuzzy set model and gray number, as well expand the sample size to enhance the objectivity of the data and credibility of the results. Additionally, subsequent research can employ structural equation modelling to analyze quantitative data and overcome the reliance on expert opinion.

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Data Availability Statement: The data generated and/or analyzed during this study are not publicly available due to privacy and our ongoing research.

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Conflicts of Interest: The authors declare no conflicts of interest.

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