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MAPPING THE BARRIERS TO CIRCULAR ECONOMY IMPLEMENTATION IN HEALTHCARE WASTE PRODUCED BY HOSPITALS IN CENTRAL JAVA PROVINCE

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Abstract:
Healthcare waste (HCW) poses significant environmental and public health risks and is growing by 2-3% annually as populations and healthcare facilities expand. HCW spans hazardous and non-hazardous streams, with sharps and chemicals requiring special handling and incurring high disposal costs. Circular Economy (CE) strategies – reduce, reuse, recycle – could mitigate these impacts, yet remain limited in healthcare, particularly in hospitals. Based on this condition, the purpose of this study examine barriers to CE adoption in hospital waste management in Central Java, Indonesia, and offers targeted recommendations. Twenty-two potential barriers were evaluated by six experts from healthcare institutions, government agencies, and professional associations using a four-point scale; Content Validity Index screening retained 16 valid items. Barrier interrelationships were then analyzed via DEMATEL to map causal links and ISM to prioritize within a hierarchical structure. The integrated DEMATEL-ISM model produced a six-level hierarchy, identifying two root causes – the absence of government legislation and high implementation costs – that drive downstream challenges, including limited incentives and organizational resistance. Mid-level barriers involve insufficient funding and systemic coordination issues, while upper levels reflect knowledge gaps and operational inefficiencies. Addressing policy and financial constraints is essential to unlock systemwide improvements. Findings underscore the need for regulatory development, financial incentives, and public education, guiding policymakers and hospital administrators toward environmentally sustainable and economically efficient HCW management.

Key words: barriers; circular economy; decision making trial and evaluation laboratory; healthcare waste; interpretive structural modeling

INTRODUCTION

The generation of Healthcare Waste (HCW) may considerably affect environmental sustainability [1] and public health [2]. Furthermore, due to an increasing population and the development of healthcare facilities [3], the worldwide generation of healthcare waste is growing at a rate of 2-3%. HCW refers to any waste generated during the delivery of healthcare services by medical facilities, such as hospitals and clinics, or by people in domestic environments. Various classifications for HCW divide the whole stream into hazardous and non-hazardous categories, accounting for 75-90% and 10-25% of the total HCW, respectively [4]. The non-hazardous component of healthcare waste, termed general healthcare waste, resembles municipal solid waste and consists of paper, plastic, glass, and food remnants and containers, predominantly generated from kitchen, administrative, and housekeeping activities within healthcare institutions [5]. In contrast to non-hazardous waste, which presents no chemical or physical

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danger, the hazardous elements of healthcare waste may result in several environmental and health risks [6]. Hazardous healthcare waste is classified according to its kind, origin, and related risk considerations about management, transportation, storage, and ultimate disposal [7]. This waste stream comprises sharps, infectious waste, expired chemical substances, medicines, anatomical and pathological waste, and radioactive waste [8]. The expenses associated with the disposal of hazardous garbage are tenfold compared to those of non-hazardous refuse [9].

The circular economy (CE) is shown in the literature as a practical approach to alleviate the detrimental environmental impacts of HCW [10, 11]. The CE technique refers to a regenerative system that reduces material input, waste, and emissions by slowing down, halting, and constraining supply chain loops [12].The design framework for the CE is increasingly implemented in industry to improve product circularity via multiple uses and recycling [13], [14] to foster product sustainability by mitigating its negative environmental impacts [15]. Exceptionally constrained CE approaches now exist inside the hospital waste management system in various forms and levels of advancement [10]. The CE approach has been highlighted in the literature as a method for reducing healthcare waste through the reuse and recycling of durable medical equipment [16], the repair and recycling of hospital instruments and surgical stainless-steel waste [11], and the replacement of disposable products with reusable alternatives in the medical and dental fields [17]. The current research emphasizes the recovery of value from disposables, such as the use of medical needles in concrete manufacturing [18].

Notwithstanding the increasing interest in CE, its implementation in the healthcare industry remains constrained. Current research mainly emphasizes Healthcare Waste Management (HWM), but wider circularity principles – such as sustainable procurement, environmentally sustainable infrastructure, and circular supply chains – remain little examined [19]. Given the complexity of the healthcare industry, integrating the CE requires a collaborative approach involving healthcare workers, policymakers, and experts in sustainability [12]. The transition to CE is significantly affected by essential behavioral and organizational aspects, notably Organizational Behavior (OB) and Environmental Education (EE), which are pivotal in determining sustainable practices within healthcare companies [20]. Furthermore, although specific studies have investigated the barriers and prospects associated with healthcare's circular transition [10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23], most of the recognized barriers and opportunities derive from analyses of literature unrelated to healthcare. Barriers to circularity in active medical devices include challenges in reprocessing, compounded by inadequate transportation and infrastructure [24], insufficient support for scaling circular economy models, substantial initial investment costs in supply chains for implementing CE practices, and elevated purchasing costs of eco-friendly materials from suppliers [22]. In this case, a specific methodology to systematically identify, structure, and analyze the intricate causal relationships among these barriers has yet to be established, as the complexity of the barriers necessitates prioritization. To the author's knowledge, a specialized integrated method that systematically discovers, constructs, and analyzes causal linkages among various barriers, such as the Decision-Making Trial and Evaluation Laboratory-Interpretive Structural Modeling (DEMATEL-ISM) method, has not previously been used in this context. These research gaps need to be addressed to clarify the hierarchy and cause-and-effect relationships among the barriers, enabling decision-makers to prioritize initiatives and formulate tailored strategies that successfully tackle the most significant barriers. Shortly, to solve the research gap, this study has several research questions.

LITERATURE REVIEW

Circular Economy

The circular economy serves as an alternative to the linear economic model defined by the "take-make-use-dispose" paradigm. A system designed to enhance the complete product life cycle, encompassing resource selection, manufacturing, use, and waste, is referred to as a circular economy. In waste management, circular economy concepts may be implemented by methods such as waste reduction, product redesign, reuse, remanufacturing, and direct recycling. The circular economy is employed to mitigate environmental contamination, decrease emission levels, and minimize waste through the application of

sustainable principles [25]. In the execution of a circular economy, trash possesses no value. Consequently, a waste processing system is required to assign a positive value to that garbage. Optimal waste management necessitates a move from a linear economy to a circular economy, founded on the concepts of reject, reduce, rethink, reuse, remanufacture, repurpose, recycle, and renew [26].

Implementation of Circular Economy in the Healthcare Sector

The healthcare sector has great potential to apply circular economy principles to reduce cost impacts and improve efficiency. In 2014, spending in the healthcare sector globally and in the European region according to the reference [27], accounted for approximately 9.9% and 9.5% of the region's Gross Domestic Product (GDP), respectively. In 2013, the global healthcare workforce exceeded 43 million people, and in the European region it reached 12.7 million people. As such, the sheer size of the healthcare sector suggests the potential for considerable cost and efficiency impacts from any move towards circular economy principles.

A study conducted on hospitals in Denmark showed the huge potential for cost savings to be obtained using two circular economy strategies, namely the use of performance models in procurement, which involve contracts by hospitals that pay for the use of products (such as leasing). This can reduce the cost of purchasing new products and improve the efficiency of resource use. In addition, hospitals can conduct training involving recycling, treatment, and waste reduction strategies and create national guidelines or targets that contain standard operating procedures (SOPs) for recycling, waste reduction, and targets to be achieved within a certain period of time. The implementation of circular economy in hospital waste management can also indirectly reduce the overall burden of disease by reducing pollution from production and consumption activities [27].

Research related to Healthcare Waste

This research identified articles published in Scopus databases with the keyword “healthcare” OR “hospital” OR “medical waste” AND “circular economy” AND “barrier” OR “challenge” in the tittle and found 72 articles. However, upon reading those articles, although not entirely appropriate, there are six articles that could support the purposes of the research and used to help in identifying the barrier to maximizing the performance of the halal industry, i.e., references [10, 23, 26, 28, 29, 30]. In detail the purpose and object of their research, methods, and the proposed barriers can be seen in Table 1.

A review of prior research on healthcare waste management reveals that, although analytical tools such as the Decision-Making Trial and Evaluation Laboratory (DEMATEL), Interpretive Structural Modeling (ISM), the Best-Worst Method (BWM), the Failure Mode and Effects Analysis (FMEA), and various fuzzy multi-criteria extensions have been widely applied, each study has focused on different system layers, sectors, or analytical objectives. Kazançoğlu et al. (2021) used a combination of Literature Review, the Fuzzy best-worst method (Fuzzy BWM), and Fuzzy VIKOR to identify barriers in the Turkish healthcare sector and to integrate big data analytics into decision-making. Jafarzadeh Ghoushchi et al. (2022) applied Failure Mode and Effects Analysis (FMEA) and Simple Multi-Objective Optimization with Full Consistency (SF-MOORA) to design a sustainable waste management framework, emphasizing operational and technological deficiencies. Mahjoob et al. (2023) employed the Decision-Making Trial and Evaluation Laboratory (DEMATEL) to analyze barriers in Miami, with a focus on supply-chain disruptions and organizational weaknesses. Tushar et al. (2023) used a combined Best–Worst Method (BWM), Interpretive Structural Modeling (ISM), and Cross-Impact Matrix Multiplication Applied to Classification (MICMAC) framework to structure barriers in Bangladesh, identifying challenges related to segregation, storage, and technology adoption.

Table 1

Summary of the Previous Research Related to Healthcare Waste Management

Author	Purpose	Object	Method	Barriers
Kane, Bakker & Balkenende (2018) [10]	Identify challenges and opportunities in tool product design.	Medical Industry	Literature Review	High cost of production, maintenance, recycling; infection risk; distrust in reprocessed tools.
Kazançoğlu et al. (2021) [28]	Identify CE barriers and apply big data analytics as solutions.	Healthcare sector, Turkey	Literature Review; Fuzzy BWM; Fuzzy VIKOR	**Economic**: high cost, low investment, unclear CE benefits; **Policy**: lack of incentives and regulation; **Organization**: poor design, low readiness; **Environment**: unsafe waste handling; **Social**: low awareness; **HR**: resistance, lack of skills; **Managerial:** weak support, stakeholder conflict.
Jafarzadeh Ghoushchi et al. (2022) [23]	Design sustainable medical waste management system.	Healthcare sector, Iran	FMEA; SFMOORA	Lack of incentives, innovation, data, cooperation, expertise, and leadership; short-term focus; poor standardization; limited funds; high costs; weak regulation.
Mahjoob, Alfadhli & Omachonu (2023) [29]	Identify and prioritize CE challenges in healthcare waste management.	Healthcare sector, Miami	Literature Review; DEMATEL	**Supply Chain**: uncertain returns, poor flexibility; **Policy**: lack of standards and incentives; **Industry**: unsustainable practices; **Technology:** weak tracking, complex CE; **Economic**: high cost, low funding; **Social:** cultural barriers, low awareness; **Internal:** weak stakeholder contribution.
Tushar et al. (2023) [30]	Identify CE barriers and propose structural solutions.	Healthcare sector, Bangladesh	BWM; ISM; MICMAC	**Operational:** poor waste segregation, limited storage; **Technology**: no tracking, no disinfection tech; **Government**: weak law enforcement, low funding; **Managerial:** lack of skills, training, and top management support.
Hoveling et al. (2024) [26]	Develop sustainable medical device designs maintaining safety and quality.	Dutch Universities of Technology	Literature Review; Expert Interviews	**Safety:** contamination risks; System: linear norms, logistical limits; **Regulation:** complex rules, privacy; Finance: cost constraints; **Technology**: poor circular design; **Social**: low acceptance, unclear roles.

Despite the extensive use of these methods, several gaps remain. Previous studies have not integrated the Content Validation Method (CVM) with a combined DEMATEL-ISM approach to first verify the relevance and appropriateness of barriers and then systematically map their causal and hierarchical relationships within hospital-generated healthcare waste systems. Nor have earlier studies conceptualized healthcare waste as part of an internal, production-like process flow within hospital operations, where regulatory and financial constraints cascade through organizational and operational levels. The novelty of the present study lies in (1) linking CVM, DEMATEL, and ISM to ensure both empirical validity and structured causal modeling; (2) constructing a multi-level hierarchy that captures the cascading influence of barriers across the healthcare waste-handling process; and (3) offering a system-based interpretation that positions healthcare waste management as an interconnected process rather than an isolated environmental problem. This condition enables the study to contribute new insights beyond

geographical context, offering a more integrated understanding of how upstream constraints shape downstream performance within hospital waste-management systems.

To contextualize this contribution, previous studies on healthcare waste have generally identified barriers across economic, technological, regulatory, social, organizational, and safety dimensions. Economic obstacles include high costs and limited investment; technological and operational issues involve weak innovation, inadequate tracking, and unsafe handling practices; regulatory challenges stem from inconsistent legislation and standardization; social and organizational issues reflect low awareness, stakeholder resistance, and insufficient cross-sector engagement; and safety concerns persist due to contamination risks and inadequate disinfection procedures. These fragmented findings underscore the need for a system-based modeling approach that captures how such barriers interact across multiple operational levels – an analytical gap that the present study addresses.

METHODOLOGY OF RESEARCH

Identify the Barriers to Circular Economy Implementation in Healthcare Waste Management

Referring to previous research, this study can identify 22 barriers to implementing the circular economy of healthcare waste produced by hospitals in Central Java Province, Indonesia.

1. Lack of government legislation and execution. The government plays a crucial role in regulating and overseeing waste management; however, ambiguity and uncertainty in existing regulations can hinder practical waste management efforts (B11).
2. Insufficient incentives, such as money, certificates, and tax reductions, can affect the motivation of hospitals, suppliers, academics, and the public to participate in sustainable and environmentally friendly practices (B12).
3. Lack of research and development (R&D) efforts to strengthen sustainability practices and create/update regulations, such as new laws (B13).
4. Organizational design that has not implemented CE principles includes structures, guidelines, and regulations not designed to support a circular economy (B21).
5. Misconceptions about the concept of sustainability (B22).
6. Lack of organizational readiness to transition to a circular economy. This readiness includes resources, infrastructure, and changes in habits toward circular practices (B23).
7. Implementing recycling is challenging due to issues of accountability, maintenance, costs, and approvals for recycled products (B31).
8. Poor infrastructure makes adapting to the shift toward circular economy practices difficult. This includes waste management processes such as separation, transportation, processing, and tracking processed waste (B32).
9. Failure to categorize waste based on its type from the source of the waste (B33).
10. Limited waste storage capacity for processing or direct disposal (B34).
11. High costs of implementing a circular economy (B41).
12. Inadequate funding allocation for implementing circular economy practices (B42).
13. Insufficient investment in applying circular economy principles (B43).
14. Lack of public commitment means the public understands the concepts but does not show adequate support, participation, or involvement in efforts to realize circular economy practices (B51).
15. Lack of public knowledge regarding the circular economy's concepts, principles, and applications (B52).
16. Inadequate safe medical waste management refers to disposal sites, transportation, packaging, technology, and procedures that do not comply with established regulations (B61).
17. The use of environmentally unfriendly medical supplies, from raw materials and packaging to single-use products, can increase waste volume (B62).
18. Limited knowledge of environmental issues among human resources (B71).

19. Lack of skills training, including waste management, procurement management, and energy efficiency training related to circular economy practices in hospitals (B72).
20. Limited human resource capacity in quantity and competence (B73).
21. Low commitment among stakeholders, which can manifest as support, involvement, and coordination among related stakeholders in adopting sustainable systems (B81).
22. Divergent interests among stakeholders (B82).

Content Validation Method

Before processing with the Combined DEMATEL-ISM methodology, a content validation method was first carried out on the 22 proposed barriers. Content validation is the process of validating and providing guarantees on whether the items (barriers) represent or depict the relevant concept [31, 32]. The step in conducting the content validation can be described as follows.

- Step 1: Prepare a validation questionnaire sheet using a four-point ordinal scale (1 = not relevant, 2 = less relevant, 3 = somewhat relevant, 4 = very relevant)
- Step 2: Determine the experts who are respondents. This study used six experts, and according to reference [33], the I-CVI threshold value for six to eight experts is at least 0.83.
- Step 3: Ask the experts to give a score according to a four-point ordinal scale on each proposed barrier, and they can also provide additional comments or barriers as suggestions for improvement.
- Step 4: Convert the score from each expert into a dichotomous value of 0 and 1. The scores of 1 and 2 convert to 0, and the scores of 3 and 4 convert to 1. Calculate the I-CVI value of each barrier and the average S-CVI value [34, 35].

Combined DEMATEL-ISM Methodology

Developed in 1971 by the Battelle Memorial Institute, the Decision-Making Trial and Evaluation Laboratory (DEMATEL) method analyzes complex systems by identifying causal relationships among factors through expert judgment [36]. It clarifies influence structures to support effective decision-making. Meanwhile, Interpretive Structural Modeling (ISM) is an interactive methodology that organizes interrelated elements – such as policies, objectives, or constraints – into a structured hierarchy based on expert input [35]. The term “interpretive” reflects reliance on expert interpretation, while “structural” emphasizes the visualization of relationships. ISM transforms complex, unclear systems into clear, graphical models that illustrate dependencies and hierarchical linkages [37]. Shortly, the DEMATEL method establishes a cause-and-effect relationship among factors, whereas the ISM method delineates the sequence of objectives within this relationship, identifies critical factors or primary factors, and characterizes each factor [38, 39, 40]. The explanation of data processing with the integration of DEMATEL-ISM can be seen as follows.

DEMATEL Methodology

- Step 1: Describe the factors and determine the intensity of the relationship between factors using the assessment scale between 0 and 4 (0 = no influence or interaction; 1 = a low influence; 2 = a moderate influence; 3 = high influence; and 4 = very high influence)
- Step 2: Create a single direct-relation matrix using Equation (1). In this case, the matrix (X) is the average of all expert's opinion values.

$$X = \begin{bmatrix} 0 & X_{12} & \cdots & X_{1n} \\ X_{21} & 0 & \cdots & a_{2n} \\ \cdots & \cdots & 0 & \cdots \\ X_{n1} & X_{n2} & \cdots & 0 \end{bmatrix} \quad (1)$$

- Step 3: Perform normalization of the direct relationship matrix using Equation (2) and (3)

$$Z = k\,X \quad (2)$$

$$k = \min\left[\frac{1}{\max i \sum_{j=1}^{n}|X_{ij}|}, \frac{1}{\max j \sum_{j=1}^{n}|X_{ij}|}\right] \quad (3)$$

- Step 4: Create a total matrix (direct and indirect relation matrix) using Equation (4)

$$T = Z(I - Z)^{-1} \quad (4)$$

- Step 5: Calculate the total rows (Di) and columns (Rj) using Equation (5) and (6)

$$D_i = \left[\sum_{j=1}^{n} T_{ij}\right]; \ (\mathrm{i} = 1, 2, \ldots, \mathrm{n}) \quad (5)$$

$$R_j = \left[\sum_{i=1}^{n} T_{ij}\right]; \ (\mathrm{j} = 1, 2, \ldots, \mathrm{n}) \quad (6)$$

- Step 6: Creating a DEMATEL causal model (DEMATEL graph) by first determining the threshold value (α). The threshold value is the average of all values in the total relationship matrix (T_c). Values below the threshold value c in the matrix (T_c) are considered to have no relationship and can be removed.

ISM Methodology

- **Step 1: Create the reachability matrix.**
  From the DEMATEL data processing, a total influence matrix (T) was generated, representing the direct and indirect effects among factors. Because T does not account for each factor's self-influence, an identity matrix (I) is added to T to produce the overall influence matrix (H), as shown in Equation (7).

$$H = T + I \quad (7)$$

- **Step 2: Perform level partitioning.**
  In this step, each barrier's *reachability set, antecedent set*, and *intersection* set are determined. The reachability set contains the barrier itself and all barriers it influences, while the antecedent set contains the barrier and all barriers that influence it. The intersection set is the overlap between the reachability and antecedent sets. Barriers with identical reachability and intersection sets are assigned to the same level in the ISM hierarchy. Once a barrier's level is determined, it is removed from the next iteration, and the process is repeated until all barriers are assigned a level.
- **Step 3: Develop the hierarchical model.**
  Using the reachability matrix and level partitioning results, a hierarchical model is constructed to categorize the barriers according to their levels in the ISM structure.

Respondent of the Research

This study involved six experts representing three key stakeholder groups to ensure diverse perspectives and a comprehensive evaluation of the barriers.

- **Company/Agency representatives** included three experts from major healthcare institutions in Central Java In this step, each barrier's *reachability set*, *antecedent set*, and *intersection set* are determined. The reachability set contains the barrier itself and all barriers it influences, while the antecedent set contains the barrier and all barriers that influence it. The intersection set is the overlap between the reachability and antecedent sets. Barriers with identical reachability and intersection sets are assigned to the same level in the ISM hierarchy. Once a barrier's level is determined, it is removed from the next iteration, and the process is repeated until all barriers are assigned a level. Diponegoro National Hospital (RSND), Dr. Kariadi General Hospital, Semarang, and Dr. Moewardi General Hospital – providing practical insights based on their operational experience in hospital waste-handling processes and environmental sustainability practices.
- **Government representatives** included one expert from the Central Java Provincial Health Office and one from the Central Java Provincial Environment and Forestry Office, each contributing policy-oriented perspectives, regulatory considerations, and strategic insights relevant to healthcare waste governance.

- **Association representatives** were drawn from the Association of Health Offices in Central Java, offering a professional community perspective and reflecting shared challenges and opportunities in hospital waste management across the province.

The inclusion of these three stakeholder groups ensured a balanced integration of operational experience, policy frameworks, and sector-wide consensus, thereby strengthening the validity and applicability of the study's findings.

In this case, the number of experts (n = 6) aligns with methodological recommendations for expert-based approaches such as the Decision-Making Trial and Evaluation Laboratory (DEMATEL) and Interpretive Structural Modeling (ISM). The literature indicates that a panel of five to ten experts is commonly recommended to ensure a diverse yet coherent range of expert judgments, while maintaining manageable group dynamics for pairwise comparisons and qualitative modeling. Several studies have successfully employed small expert samples, including four experts [41, 42], demonstrating that expert-judgment methods remain robust even with limited sample sizes when participants possess high domain expertise. Shieh et al. [43] highlight that a smaller group can maintain optimal data-processing efficiency without compromising depth of insight. Additional evidence shows that DEMATEL can produce reliable outcomes with small panels [36, 44], and some studies consider three experts sufficient to achieve stable causal interpretations [45]. For ISM specifically, 3-7 experts are typically consulted [41, 46, 47], as the method is qualitative and focuses on constructing a structural model rather than statistical generalization.

Then, the experts in this study were selected using a purposive sampling approach, guided by criteria emphasizing domain relevance and professional competence. Each expert met the following requirements:

- A minimum of five years of professional experience in healthcare waste management, hospital operations, or environmental health.
- Direct responsibility for implementing, supervising, or evaluating waste-handling procedures; and
- Familiarity with both operational and regulatory frameworks governing healthcare waste.

These criteria ensured that the expert panel consisted of individuals with specialized knowledge essential for structured expert-based assessment techniques, thereby confirming that the sample size was methodologically appropriate and fully aligned with established practices in DEMATEL-ISM research.

RESULTS OF RESEARCH

Result of Content Validity Index

The results of the validation with content validation method can be seen in Table 2.

Table 2

The Result of Content Validation Process

Barriers	Result from Questionnaires						Convert to binary number						Agreement	I-CVI
	E1	E2	E3	E4	E5	E6	E1	E2	E3	E4	E5	E6		
B11	4	3	3	2	4	3	1	1	1	0	1	1	5	0.833
B12	4	3	3	4	3	3	1	1	1	1	1	1	6	1.000
B13	2	4	3	3	2	3	0	1	1	1	0	1	4	0.667
B21	3	4	4	4	3	3	1	1	1	1	1	1	6	1.000
B22	2	3	3	3	2	3	0	1	1	1	0	1	4	0.667
B23	4	3	4	3	3	3	1	1	1	1	1	1	6	1.000
B31	4	4	3	4	3	3	1	1	1	1	1	1	6	1.000
B32	3	3	3	4	3	3	1	1	1	1	1	1	6	1.000
B33	3	2	3	3	3	2	1	0	1	1	1	0	4	0.667

cont. table 2

B34	2	3	3	3	2	2	0	1	1	1	0	0	3	0.500
B41	4	4	4	4	4	4	1	1	1	1	1	1	6	1.000
B42	3	3	3	4	3	4	1	1	1	1	1	1	6	1.000
B43	2	2	3	3	3	3	0	0	1	1	1	1	4	0.667
B51	3	4	4	4	3	2	1	1	1	1	1	0	5	0.833
B52	3	4	3	4	2	4	1	1	1	1	0	1	5	0.833
B61	3	4	4	3	3	4	1	1	1	1	1	1	6	1.000
B62	4	3	4	4	4	3	1	1	1	1	1	1	6	1.000
B71	3	4	4	3	4	3	1	1	1	1	1	1	6	1.000
B72	3	4	3	4	4	3	1	1	1	1	1	1	6	1.000
B73	4	4	3	4	2	2	1	1	1	1	0	0	4	0.667
B81	4	3	4	4	3	4	1	1	1	1	1	1	6	1.000
B82	1	4	4	3	4	4	0	1	1	1	1	1	5	0.833
Initial S-CVI														0.871
Final S-CVI														0.958

E1 until E6 are expert 1 until expert 6, representative from three group of stakeholders.

The content validity assessment conducted with six experts generated item-level CVI (I-CVI) scores for 22 barriers and allowed objective filtering based on predefined acceptance thresholds. Barriers with I-CVI = 1.00 (high-agreement) were retained without modification; these included insufficient incentives, organizational readiness deficiencies, recycling and infrastructure limitations, high implementation costs, limited funding, unsafe waste practices, low environmental knowledge, inadequate training, and weak stakeholder commitment. Barriers with I-CVI = 0.83 (moderate agreement; 5 of 6 experts), such as weak legislation, low public awareness, and conflicting stakeholder interests, were retained and noted for further clarification during subsequent stages. Items with I-CVI ≤ 0.67 (weak agreement) did not satisfy minimum content validity requirements and were eliminated from further analysis. This filtering increased the scale-level CVI (S-CVI) from 0.871 to 0.958, indicating excellent overall content validity and reducing the final barrier set from 22 to 16. **Basically, this CVM procedure ensured cross-expert consistency by retaining only those barriers that met established validity thresholds before inclusion in the DEMATEL-ISM causal-structuring process.**

Result of Data Processing with Integration DEMATEL-ISM

The data processing stage using the integrated DEMATEL-ISM method begins with the calculation of the **Direct Relation Matrix** based on Equation (1), in which X_{ij} represents the average score assigned by all experts regarding the influence of barrier i on barrier j. Before aggregation, expert input in the DEMATEL stage was checked for consistency through a structured three-step procedure. First, each expert's pairwise comparison matrix was examined for internal contradictions, such as illogical directional influences or extreme inconsistencies. Second, expert judgments were aggregated using the average of normalized matrices, a standard procedure that minimizes the impact of individual deviations and highlights shared causal patterns across respondents. Third, any inconsistencies, missing values, or unclear pairwise scores were clarified through follow-up verification with the experts to ensure that the finalized Direct Relation Matrix accurately reflected their intended evaluations. Table 3 indicated the Direct Relation Matrix.

Table 3
Direct Relation Matrix

Barriers	B11	B12	B21	B23	B31	B32	B41	B42	B51	B52	B61	B62	B71	B72	B81	B82	
B11		3.333	3.833	3.833	3.333	3.500	2.833	3.667	3.667	3.833	3.500	3.000	3.167	3.000	3.500	3.167	51.167
B12	1.333		3.333	3.000	2.667	2.333	0.167	0.667	3.667	3.333	2.833	2.833	2.000	2.000	2.833	2.833	35.833
B21	1.000	1.167		3.000	1.667	0.833	0.167	2.333	2.667	0.167	2.667	3.167	3.000	3.000	2.833	2.500	30.167
B23	0.500	0.667	3.000		2.333	0.833	0.667	2.167	2.667	0.167	3.333	3.167	3.167	3.000	2.833	2.167	30.667
B31	1.167	1.167	1.167	0.167		1.167	1.000	0.833	0.500	0.000	2.500	3.000	1.000	0.667	0.667	0.500	15.500
B32	0.667	2.167	3.667	3.167	3.333		0.833	3.667	0.500	2.833	3.167	3.000	2.333	0.833	0.833	1.000	32.000
B41	3.500	3.667	3.167	3.000	3.333	3.833		3.833	3.333	0.667	3.500	3.500	2.667	3.667	3.000	2.833	47.500
B42	1.333	1.333	0.833	2.167	3.167	3.000	1.000		0.333	0.000	3.333	3.000	2.500	3.333	0.333	0.333	26.000
B51	0.167	0.167	0.000	0.000	2.333	0.000	0.000	0.000		3.333	2.500	2.833	0.500	3.500	0.167	0.167	15.667
B52	0.000	0.000	0.000	0.000	2.500	0.000	0.000	0.000	3.333		2.500	3.000	0.333	3.500	0.167	0.167	15.500
B61	1.000	1.000	0.000	0.500	2.500	0.000	0.667	1.833	1.000	0.000		2.500	0.167	0.500	0.667	0.667	13.000
B62	0.667	0.333	0.500	0.000	2.500	0.333	0.667	1.833	0.000	0.000	3.167		0.333	0.667	0.167	0.500	11.667
B71	0.333	0.333	1.833	0.833	2.167	1.000	0.167	0.167	0.000	0.000	3.167	2.000		3.167	0.500	0.500	16.167
B72	0.000	0.000	0.000	0.000	2.833	2.667	1.000	0.167	2.500	2.500	3.167	2.000	3.333		0.500	0.500	21.167
B81	0.333	0.333	2.833	3.000	2.833	1.000	1.167	2.667	0.667	0.333	2.667	3.167	1.333	2.667		3.333	28.333
B82	0.333	0.333	2.833	3.000	2.833	1.000	1.167	2.667	0.667	0.333	3.333	3.167	1.333	3.167	3.333		29.500
Total	12.333	16.000	27.000	25.667	40.333	21.500	11.500	26.500	25.500	17.500	45.333	43.333	27.167	36.667	22.333	21.167	

The next stage in data processing using the DEMATEL-ISM integration is normalization of the Direct Relation Matrix using Equations (2) and (3). Normalization ensures that the influence values assigned by experts are scaled consistently, making them comparable across all barriers. Once the matrix is normalized, the **total relation matrix**, which incorporates both direct and indirect influences among the barriers, is calculated using Equation (4). The Normalized Direct Relation Matrix and Total Relation Matrix can be seen in Table 4 and Table 5.

Table 4

Normalized Direct Relation Matrix

Barries	B11	B12	B21	B23	B31	B32	B41	B42	B51	B52	B61	B62	B71	B72	B81	B82
B11	0.000	0.065	0.075	0.075	0.065	0.068	0.055	0.072	0.072	0.075	0.068	0.059	0.062	0.059	0.068	0.062
B12	0.026	0.000	0.065	0.059	0.052	0.046	0.003	0.013	0.072	0.065	0.055	0.055	0.039	0.039	0.055	0.055
B21	0.020	0.023	0.000	0.059	0.033	0.016	0.003	0.046	0.052	0.003	0.052	0.062	0.059	0.059	0.055	0.049
B23	0.010	0.013	0.059	0.000	0.046	0.016	0.013	0.042	0.052	0.003	0.065	0.062	0.062	0.059	0.055	0.042
B31	0.023	0.023	0.023	0.003	0.000	0.023	0.020	0.016	0.010	0.000	0.049	0.059	0.020	0.013	0.013	0.010
B32	0.013	0.042	0.072	0.062	0.065	0.000	0.016	0.072	0.010	0.055	0.062	0.059	0.046	0.016	0.016	0.020
B41	0.068	0.072	0.062	0.059	0.065	0.075	0.000	0.075	0.065	0.013	0.068	0.068	0.052	0.072	0.059	0.055
B42	0.026	0.026	0.016	0.042	0.062	0.059	0.020	0.000	0.007	0.000	0.065	0.059	0.049	0.065	0.007	0.007
B51	0.003	0.003	0.000	0.000	0.046	0.000	0.000	0.000	0.000	0.065	0.049	0.055	0.010	0.068	0.003	0.003
B52	0.000	0.000	0.000	0.000	0.049	0.000	0.000	0.000	0.065	0.000	0.049	0.059	0.007	0.068	0.003	0.003
B61	0.020	0.020	0.000	0.010	0.049	0.000	0.013	0.036	0.020	0.000	0.000	0.049	0.003	0.010	0.013	0.013
B62	0.013	0.007	0.010	0.000	0.049	0.007	0.013	0.036	0.000	0.000	0.062	0.000	0.007	0.013	0.003	0.010
B71	0.007	0.007	0.036	0.016	0.042	0.020	0.003	0.003	0.000	0.000	0.062	0.039	0.000	0.062	0.010	0.010
B72	0.000	0.000	0.000	0.000	0.055	0.052	0.020	0.003	0.049	0.049	0.062	0.039	0.065	0.000	0.010	0.010
B81	0.007	0.007	0.055	0.059	0.055	0.020	0.023	0.052	0.013	0.007	0.052	0.062	0.026	0.052	0.000	0.065
B82	0.007	0.007	0.055	0.059	0.055	0.020	0.023	0.052	0.013	0.007	0.065	0.062	0.026	0.062	0.065	0.000

Table 5

Total Relation Matrix

Barriers	B11	B12	B21	B23	B31	B32	B41	B42	B51	B52	B61	B62	B71	B72	B81	B82	D
B11	0.028	0.095	0.126	0.123	0.152	0.110	0.079	0.126	0.122	0.107	0.167	0.153	0.118	0.135	0.111	0.103	1.856
B12	0.041	0.019	0.097	0.089	0.110	0.069	0.020	0.050	0.104	0.086	0.121	0.119	0.075	0.090	0.083	0.082	1.257
B21	0.033	0.038	0.030	0.083	0.083	0.040	0.019	0.075	0.076	0.022	0.108	0.113	0.090	0.100	0.078	0.071	1.060
B23	0.024	0.029	0.084	0.027	0.095	0.040	0.028	0.072	0.076	0.021	0.120	0.113	0.092	0.099	0.077	0.064	1.062
B31	0.032	0.034	0.039	0.020	0.028	0.036	0.028	0.035	0.025	0.011	0.078	0.085	0.036	0.034	0.027	0.024	0.573
B32	0.030	0.061	0.100	0.089	0.116	0.026	0.031	0.103	0.041	0.070	0.121	0.115	0.080	0.063	0.043	0.045	1.135
B41	0.092	0.102	0.113	0.108	0.149	0.117	0.026	0.128	0.112	0.049	0.162	0.157	0.108	0.141	0.101	0.096	1.760
B42	0.040	0.043	0.043	0.064	0.105	0.080	0.033	0.029	0.031	0.018	0.114	0.103	0.078	0.096	0.028	0.027	0.932
B51	0.009	0.009	0.007	0.005	0.067	0.009	0.006	0.010	0.013	0.072	0.072	0.076	0.021	0.082	0.010	0.010	0.479
B52	0.006	0.006	0.006	0.005	0.069	0.009	0.006	0.010	0.074	0.010	0.071	0.079	0.018	0.081	0.009	0.009	0.467
B61	0.027	0.028	0.014	0.022	0.070	0.013	0.020	0.049	0.031	0.009	0.026	0.072	0.018	0.028	0.024	0.023	0.475
B62	0.021	0.016	0.020	0.011	0.067	0.018	0.020	0.048	0.010	0.006	0.082	0.022	0.019	0.028	0.013	0.018	0.418
B71	0.014	0.016	0.048	0.029	0.067	0.032	0.011	0.020	0.015	0.009	0.089	0.065	0.018	0.078	0.022	0.021	0.555
B72	0.010	0.012	0.017	0.014	0.086	0.063	0.027	0.022	0.063	0.060	0.096	0.073	0.080	0.026	0.021	0.021	0.690
B81	0.022	0.024	0.082	0.084	0.102	0.044	0.037	0.083	0.039	0.021	0.106	0.112	0.059	0.091	0.026	0.086	1.016
B82	0.022	0.024	0.082	0.084	0.104	0.044	0.038	0.084	0.040	0.022	0.120	0.114	0.060	0.101	0.087	0.025	1.050
R	0.451	0.556	0.909	0.857	1.471	0.751	0.429	0.945	0.871	0.594	1.654	1.572	0.968	1.273	0.759	0.725	

This step allows for the identification not only of immediate relationships but also of the extended effects that one barrier may exert on others through intermediary factors. Following this, the values of (Di+Ri) and (Di-Ri) (use Equation (5) and (6)) are computed for each barrier, as shown in Table 6.

Table 6
Total Di+Ri, and Di-Ri for the Barriers

Barriers	R (total in column)	D (total in row)	Di + Ri	Di - Ri	Category
B11	0.451	1.856	2.306	1.405	Cause
B12	0.556	1.257	1.813	0.701	Cause
B21	0.909	1.060	1.969	0.150	Cause
B23	0.857	1.062	1.919	0.205	Cause
B31	1.471	0.573	2.043	-0.898	Effect
B32	0.751	1.135	1.886	0.385	Cause
B41	0.429	1.760	2.189	1.331	Cause
B42	0.945	0.932	1.877	-0.013	Effect
B51	0.871	0.479	1.350	-0.392	Effect
B52	0.594	0.467	1.061	-0.126	Effect
B61	1.654	0.475	2.129	-1.180	Effect
B62	1.572	0.418	1.990	-1.154	Effect
B71	0.968	0.555	1.523	-0.413	Effect
B72	1.273	0.690	1.964	-0.583	Effect
B81	0.759	1.016	1.775	0.257	Cause
B82	0.725	1.050	1.775	0.325	Cause

Here, (Di+Ri) represents the prominence of a barrier, indicating the overall degree of involvement of a factor in the system – both in terms of exerting influence on others and being influenced by them. Meanwhile, (Di-Ri) is used to distinguish between cause factors (those with a positive value, meaning they exert more influence than they receive) and effect factors (those with a negative value, meaning others have more influence on them than they have on others). These values serve as the foundation for plotting the cause-and-effect diagram, which visually illustrates the directional relationships and interaction strengths among the barriers (see Fig. 1).

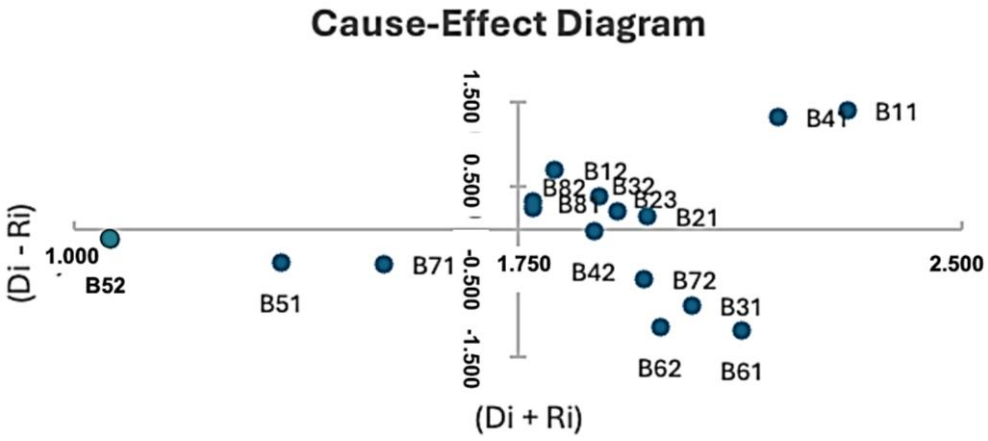


Fig. 1 Cause-Effect Diagram

Alt-text: *Cause-effect diagram illustrating 16 barriers to circular economy implementation in healthcare waste management based on their prominence (Di + Ri) and net causal influence (Di − Ri). The diagram is divided into four quadrants. The upper-right quadrant contains B11, B12, B21, B23, B32, B41, B81, and B82, representing barriers with high prominence and positive causal influence. The lower-right quadrant contains B31, B42, B61, B62, and B72, representing barriers with high prominence and negative causal influence. The lower-left quadrant contains B51, B52, and B71, representing barriers with lower prominence and negative causal influence. No barriers are located in the upper-left quadrant.*

The results show that several barriers fall into the cause category, with the most influential being lack of government legislation and execution (B11) and high implementation costs (B41). These two factors stand out as the strongest drivers of other challenges, while insufficient incentives (B12), lack of organizational readiness (B23), organizational design not aligned with circular economy principles (B21), poor infrastructure (B32), low stakeholder commitment (B81), and divergent stakeholder interests (B82) also appear as significant causal factors. In contrast, barriers categorized as effects include inadequate medical waste management (B61) and the use of environmentally unfriendly medical supplies (B62), which are the most heavily influenced by upstream issues. Other effect barriers such as recycling challenges (B31), lack of skills training (B72), limited environmental knowledge (B71), lack of public commitment (B51), lack of public knowledge (B52), and inadequate funding allocation (B42) also reflect downstream consequences of systemic weaknesses. Overall, these results emphasize that regulatory, financial, institutional, and stakeholder-related issues act as root causes, while technical and operational problems emerge as their effects. Addressing the causal barriers is therefore essential to generate wider improvements across the system.

From the DEMATEL analysis, the Total Relation Matrix was derived by combining the direct and indirect influence relationships among all barrier factors. Using this matrix, the Overall Influence Matrix (H) was generated and then transformed into a Reachability Matrix by applying a threshold value of 0.058, calculated as the average of all elements in the Total Relation Matrix (see Table 5 for Total Relation Matrix). Elements below the threshold were assigned a value of 0 (no significant relationship), while those equal to or above were assigned 1 (strong relationship). The Reachability Matrix was subsequently used in the ISM process to classify barriers into three sets: the reachability set, antecedent set, and intersection set. The reachability set includes all factors influenced by a given barrier (indicated by "1" in its row), while the antecedent set represents those factors that influence it (indicated by "1" in its column). The intersection set reflects the overlap between the two. Within ISM, these sets serve as the foundation for establishing hierarchical levels. When the reachability and intersection sets are identical, the barrier is classified at Level 1, representing the most dependent factors. The process is repeated iteratively until all levels are identified, forming a comprehensive multi-level structural model of interrelated barriers (see Table 7).

Table 7
Level Partitioning

Barriers	Reachability Set	Antecedent Set	Intersection Set	Level
B31	31,61,62	11,12,21,23,31,32,41,42,51,52,61,62,71,72,81,82	31,61,62	1
B61	31,61,62	11,12,21,23,31,32,41,42,51,52,61,62,71,72,81,82	31,61,62	1
B62	31,61,62	11,12,21,23,31,32,41,42,51,52,61,62,71,72,81,82	31,61,62	1
B51	51,52,72	11,12,21,23,41,51,52,72	51,52,72	2
B52	51,52,72	11,12,32,51,52,72	51,52,72	2
B71	71,72	11,12,21,23,32,41,42,71,72,81,82	71,72	2
B72	32,51,52,71,72	11,12,21,23,32,41,42,51,52,71,72,81,82	32,51,52,71,72	2
B42	23,42	11,21,23,41,42,81,82	23,42	3
B21	21,81,82	11,12,21,41,81,82	21,81,82	4
B23	21,81,82	11,12,21,41,81,82	21,81,82	4
B81	21,81,82	11,12,21,41,81,82	21,81,82	4
B82	21,81,82	11,12,2141,81,82	21,81,82	4
B12	12	11,12,41	12	5
B32	12	11,12,41	12	5
B11	11,41	11,41	11,41	6
B41	11,41	11,41	11,41	6

After assigning all barrier factors to their respective levels (see Table 5), the integrated DEMATEL-ISM model was constructed by combining the hierarchical structure from ISM with causal influence strengths

from DEMATEL. This integration provides a comprehensive view of both the position and influence magnitude of each barrier. Barriers at lower levels act as key drivers, while upper-level barriers are more dependent. The model simplifies complex interrelationships, helping policymakers and researchers identify root causes that require priority action. Once these foundational barriers are addressed, dependent barriers at higher levels are expected to improve (see Fig. 2).

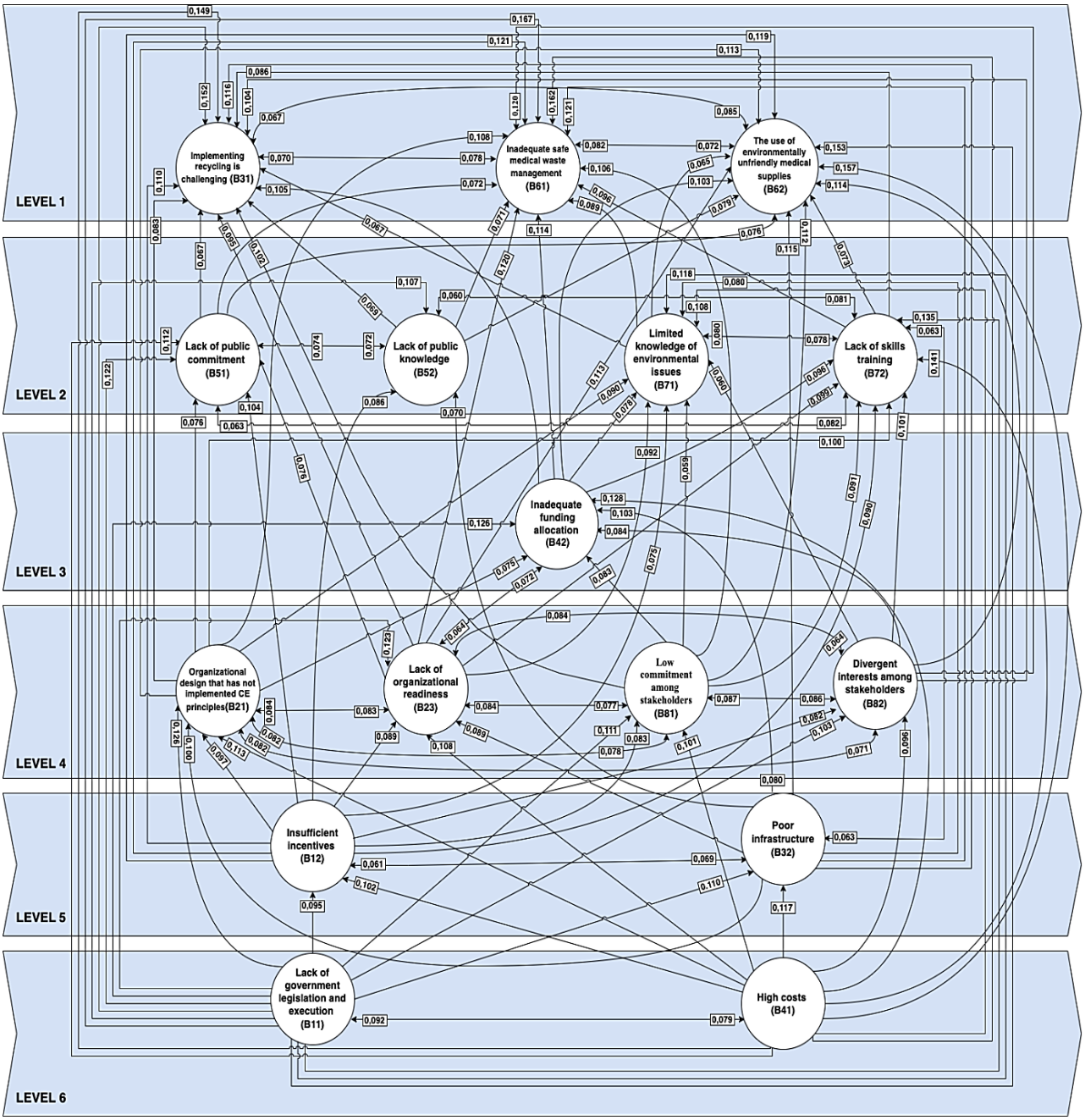


Fig. 2 Diagraph DEMATEL-ISM

Alt-text: *DEMATEL-ISM digraph illustrating the hierarchical relationships among 16 barriers to circular economy implementation in healthcare waste management. The model consists of six hierarchical levels. Level 1 includes B31 (Implementing recycling challenging), B61 (Inadequate medical waste management), and B62 (The use of environmentally unfriendly medical supplies). Level 2 includes B51 (Lack of public commitment), B52 (Lack of public knowledge), B71 (Limited knowledge of environmental issues), and B72 (Lack of skills training). Level 3 includes B42 (Inadequate funding allocation). Level 4 includes B21 (Organizational design that has not implemented CE principles), B23 (Lack of organizational readiness), B81 (Low commitment among stakeholders), and B82 (Divergent interests among stakeholders). Level 5 includes B12 (Insufficient incentives) and B32 (Poor infrastructure). Level 6 includes B11 (Lack of government legislation and execution) and B41 (High costs). Arrows indicate the directional relationships and influence among the barriers across the hierarchical levels.*

The integrated DEMATEL-ISM model reveals a six-level hierarchical structure of barriers to circular economy implementation for healthcare waste in hospital, with case study Central Java Province, Indonesia.

a. At the deepest level (Level 6) lie the root causes, namely the lack of government legislation and execution (B11) and the high costs of implementation (B41). These two barriers exert the most decisive influence across the system, shaping incentives, organizational structures, and ultimately operational practices. Without clear regulations and financial feasibility, downstream improvements remain unsustainable.
b. Moving upward, Level 5 contains insufficient incentives (B12). This barrier is strongly shaped by policy and cost structures but also influences organizational readiness and stakeholder commitment.
c. At Level 4, several systemic and organizational issues emerge, including organizational design not aligned with CE principles (B21), lack of organizational readiness (B23), poor infrastructure (B32), and stakeholder-related challenges such as low commitment (B81) and divergent interests (B82). They form a bridge between macro-level policies/costs and micro-level operational issues. These barriers highlight the structural weaknesses that mediate between policy-level deficiencies and practical implementation obstacles.
d. Level 3 is occupied by inadequate funding allocation (B42), which directly reflects the translation of high costs and weak policy support into limited financial capacity at the organizational level.
e. At Level 2, the model identifies knowledge and capacity-related constraints: lack of public commitment (B51), lack of public knowledge (B52), limited knowledge of environmental issues (B71), and lack of skills training (B72). These issues represent human and societal barriers that depend heavily on stronger structures, funding, and stakeholder alignment.
f. Finally, Level 1 consists of the most dependent barriers, including recycling challenges (B31), inadequate medical waste management (B61), and the use of environmentally unfriendly medical supplies (B62). These are the most visible barriers in practice, yet the model shows they are outcomes rather than primary drivers.
g. The cause – and – effect dynamics provide further insights into how these barriers interact.
   - Strong causal factors: The most powerful drivers identified are lack of government legislation and execution (B11) and high costs of implementation (B41). These two barriers exert the greatest systemic influence, and without effective legislation, enforcement, and cost management, improvements in downstream barriers are unlikely to be sustainable.
   - Bridging factors: Several barriers act as connectors between macro-structural causes and micro-operational effects. These include organizational design not aligned with circular economy principles (B21), lack of organizational readiness (B23), poor infrastructure (B32), low commitment among stakeholders (B81), and divergent interests among stakeholders (B82). The presence of these barriers suggests that even if policies and financial resources are improved, weak organizational structures, inadequate readiness, or poor stakeholder collaboration could still block effective implementation of circular economy practices.
   - Effect factors: At the dependent end of the hierarchy, the model identifies recycling challenges (B31), inadequate safe medical waste management (B61), and the use of environmentally unfriendly medical supplies (B62) as highly dependent barriers. These are the most visible issues in practice, but the analysis shows they are outcomes of deeper systemic problems. Direct interventions here, such as introducing new recycling technologies or improving medical waste handling, will not be sustainable unless the upstream causes are first resolved.

Taken together, the hierarchy reveals a top-down causal chain where policy and financial barriers drive organizational weaknesses, knowledge gaps, and operational inefficiencies. Addressing root causes-legislation, financing, and organizational readiness – enables systemic improvement. The integrated DEMATEL-ISM model highlights multi-level, coordinated strategies for sustainable and scalable medical waste management reform

DISCUSSION

The strategic recommendations, derived from the integrated DEMATEL-ISM analysis of circular economy adoption in healthcare waste management in Central Java hospitals, address two key barriers: lack of government legislation and high implementation costs. Expert validation confirms that tackling these root issues is vital for achieving sustainable healthcare waste management.

a. Lack of Government Legislation and Execution. To address this barrier, a multi-faceted policy approach is recommended.

- Governments need to develop supportive policies and regulations that encourage waste reduction and recycling practices in healthcare institutions. This includes setting standards and guidelines for sustainable hospital waste management, with measurable indicators such as emissions generated from incineration or disposal processes [27].
- A systematic monitoring and evaluation system is also required to track every stage of waste management, from collection to treatment. Such a system would enable early detection of problems, allowing corrective measures before they escalate into public health or environmental risks. Evaluation mechanisms would also help identify best practices and areas requiring improvement [27].
- Financial mechanisms are another key component. The government could provide funding and incentives for hospitals, such as through performance-based regional grants, rewarding hospitals that actively reduce waste and applying disincentives – including public performance disclosure and administrative sanctions – for those failing to comply [48].
- Medical equipment manufacturers could be incentivized to design products that are more durable, repairable, and recyclable, aligning production with circular economy principles [27]. Research support is also essential. Governments should fund studies on the health impacts of recycled materials, providing a scientific foundation for regulations and building public trust in safe reuse practices. In parallel, public education campaigns can reshape perceptions about the quality and safety of refurbished or recycled medical products while promoting sustainable consumption models such as reuse and shared-use systems [27].
- Collaboration across ministries and stakeholders is equally important. Agencies such as the Ministry of Investment and the Ministry of State-Owned Enterprises should actively support the expansion of recycling facilities, including those serving hospitals [49]. Finally, a National Circular Economy Action Plan (NCEAP) should be established, specifically targeting the healthcare sector. This plan should involve stakeholders from civil society, intergovernmental organizations, private industry, media, and academia, ensuring a holistic and coordinated approach to advancing circular economy adoption [27].

b. High Costs of Implementation. To mitigate these barriers, several cost-saving and innovative strategies are proposed.

- Hospitals can adopt green infrastructure initiatives, such as planting carbon-absorbing vegetation in open spaces. Productive plants (e.g., cabbage, pumpkin, grapes, melons) can be cultivated, with harvests incorporated into hospital nutrition services, benefiting both patients and staff. Establishing green hospital teams, composed of representatives from different units, can further institutionalize daily efficiency programs. These teams can monitor and evaluate initiatives through smartphone applications, embedding sustainability into everyday operations [50].
- For waste reduction, hospitals may apply bioconversion technologies using Black Soldier Fly (BSF) larvae to process organic waste into valuable by-products such as animal feed [51]. Additionally, hospitals can implement refurbishing and recycling practices for stainless steel instruments and other reusable materials. Equipment that cannot be repaired can still be recycled through authorized waste management services [26].
- Capacity building is also essential. Hospital training units can introduce specialized training programs to reduce waste and adopt recycling practices, producing both environmental and

financial benefits. Furthermore, hospitals should consider leasing medical technologies rather than purchasing them outright. Examples include MRI scanners, radiation therapy devices, laboratory instruments, and semi-durable equipment such as surgical knives and gowns. Performance-based procurement models have been shown to save hospitals in Denmark € 70-90 million by 2035, reducing both upfront investment and long-term maintenance costs [27].

Policymakers must soon strengthen regulations, provide financial incentives, and foster multi-stakeholder collaboration. Meanwhile, hospitals must adopt innovative practices that integrate sustainability into their daily operations. By combining regulatory reforms with cost-efficient practices, the healthcare sector can establish a supportive ecosystem for circular economy adoption, leading to long-term improvements in environmental quality, public health, and financial sustainability.

In hospital operations, waste is not merely a residual output but an inherent part of the service-production process. Every clinical and non-clinical activity generates material flows that move through interdependent stages – waste generation, segregation, storage, transportation, treatment, and value recovery – making waste management an integral subsystem within the hospital's overall operational process. By viewing waste in this way, the integrated DEMATEL-ISM analysis reveals how strategic-level barriers, such as inadequate regulation and high costs, disrupt the continuity of these interconnected stages, much like upstream constraints in a production system that impair downstream performance.

The recommendations related to legislation, monitoring systems, incentives, and inter-ministerial coordination strengthen the system's enabling conditions, allowing the early stages of the waste-handling process to function without interruption. These measures improve overall process control, reduce variability, and increase reliability across the chain. Similarly, cost-related strategies – such as green infrastructure initiatives, bioconversion technologies, refurbishment, and equipment leasing – target inefficiencies at the operational level. They optimize resource use, reduce unnecessary inputs, and enhance process efficiency in ways comparable to improvement practices in production operations.

Viewed collectively, the proposed interventions not only address environmental and organizational aspects but also reinforce the integrity of the entire waste-management system. They help realign the process flow, remove upstream bottlenecks, and stabilize downstream activities. This systems-based interpretation positions the recommendations within a broader process-management framework, demonstrating that the transition towards a circular economy in hospitals requires coordinated improvements across strategic, structural, and operational layers – an approach consistent with analytical traditions in production engineering.

To strengthen the practical relevance of the findings, this study also identifies a set of organizational and technical measures that hospitals can directly implement. These measures illustrate how circular-economy adoption in healthcare waste management can be systematically embedded into process management and production engineering practices.

Organizational Measures

At the organizational level, hospitals can institutionalize circular economy in healthcare waste management by establishing dedicated Circular Economy-Healthcare Waste Management (CE-HWM) units to oversee segregation accuracy, monitor material recovery, and integrate CE-HWM criteria into procurement, logistics, and facility-management workflows. Embedding CE-HWM responsibilities into departmental performance indicators – for example: housekeeping segregation-compliance scores, laboratory hazardous/non-hazardous segregation accuracy, surgery-unit instrument recovery or refurbishment rates – can reduce cross-unit variability and strengthen accountability.

Likewise, process-management tools commonly used in industrial engineering – value-stream mapping for waste flows, failure-mode analysis for segregation errors, and PDCA cycles for continuous improvement – can be adapted to improve the reliability of the hospital waste-handling process.

Technical Measures and CE-HWM Efficiency Indicators

Technically, hospitals can adopt CE efficiency indicators explicitly tailored to healthcare waste management. Relevant indicators include:

- segregation-accuracy rate per department;
- percentage of recyclables or recoverable from total healthcare waste;
- reduction in incineration volume per patient-day;
- average refurbishment cycles for reusable medical instruments;
- share of leased vs. purchased medical equipment;
- energy use per kilogram of treated healthcare waste;
- cost savings from refurbishment, leasing, or material recovery;
- carbon-intensity reduction from green-infrastructure initiatives or BSF-based bioconversion.

Integrating these indicators into digital dashboards or automated monitoring systems enables hospitals to evaluate performance in real time, identify deviations early, and design data-driven interventions to strengthen CE-HWM outcomes.

Technological Measures

Technological solutions can further accelerate circular economy adoption in healthcare waste management. RFID or barcode-based waste tagging, IoT-enabled monitoring of waste-bin volume and temperature, and digital segregation-audit applications enhance traceability and process control across the waste-handling chain. These tools function similarly to production-engineering control systems, ensuring that deviations in waste flow are detected and corrected before they disrupt downstream stages..

CONCLUSION

Based on the literature review and Content Validity Index (CVI) assessment, 16 out of 22 barrier factors in implementing a circular economy (CE) for hospital waste management in Central Java were validated and analysed using the integrated DEMATEL-ISM method. The DEMATEL results identified two variable categories: cause and effect. Cause-type barriers include lack of government legislation and execution, insufficient incentives, non-CE-oriented organizational design, inadequate readiness, weak infrastructure, high costs, low stakeholder commitment, and conflicting interests. Effect-type barriers consist of recycling difficulties, inadequate funding, low public commitment and knowledge, unsafe medical waste management, use of non-eco-friendly medical supplies, limited environmental understanding, and lack of skills training.

The ISM analysis classified barriers into six hierarchical levels. **Level 1** includes recycling difficulty, unsafe waste management, and non-environmentally friendly supplies. **Level 2** comprises low public commitment and knowledge, limited environmental understanding, and a lack of training. **Level 3** includes inadequate funding. **Level 4** covers weak organizational design and readiness, low stakeholder commitment, and conflicting interests. **Level 5** includes insufficient incentives, while Level 6 comprises a lack of legislation and high costs. These highest-level barriers indicate systemic and policy-related challenges that influence all other levels.

The priority barriers identified through the integrated DEMATEL-ISM model are the lack of legislation and government execution, and high costs. To address these, recommendations include developing comprehensive CE policies, improving monitoring and enforcement, creating incentive schemes for hospitals and manufacturers, promoting research on recycled medical materials, and enhancing public education and recycling infrastructure. For cost barriers, hospitals can adopt low-cost green initiatives such as forming green hospital teams, utilizing refurbished or recycled materials, managing organic waste, and implementing health technology leasing to reduce capital expenditure.

The findings provide practical implications for policymakers, hospital administrators, and industry stakeholders. Policymakers should strengthen regulatory frameworks and incentive mechanisms to

accelerate CE adoption. At the same time, hospitals can implement waste-to-resource innovations – such as bioconversion, refurbishing, and recycling initiatives – and enhance staff capability through structured training programs. To reinforce operational applicability, this study further outlines organizational and technical measures that hospitals can directly implement to embed circular-economy principles into daily healthcare-waste-management practices. At the organizational level, hospitals can establish dedicated CE-HWM units to monitor segregation accuracy, oversee material recovery processes, and integrate CE-HWM criteria into procurement, logistics, and facility management workflows. Embedding these responsibilities into departmental performance indicators – such as housekeeping compliance scores, laboratory segregation accuracy, or refurbishment rates in surgical units – can reduce cross-unit variability and strengthen accountability.

Technically, hospitals may adopt CE-oriented efficiency indicators tailored to healthcare waste, such as segregation-accuracy rates per department, recovery percentages, reductions in incineration volume per patient-day, refurbishment cycles for reusable medical instruments, the ratio of leased to purchased equipment, energy consumption per kilogram of treated waste, cost savings generated from material recovery, and carbon reductions from green-infrastructure or BSF-based bioconversion initiatives. These indicators, when embedded into digital dashboards or automated monitoring systems, enable real-time tracking, early deviation detection, and data-driven decision-making. Complementary technological tools – such as RFID or barcode-based waste tagging, IoT-enabled monitoring of waste-bin volume and temperature, and digital segregation-audit applications – further enhance traceability and process control, ensuring the continuity and stability of waste-handling stages.

From a theoretical perspective, this study advances circular-economy scholarship in the healthcare sector by integrating Content Validation Method with DEMATEL-ISM, ensuring methodological rigor and enhancing the reliability of barrier identification. The approach distinguishes between structural and institutional (cause-type) barriers – such as regulatory gaps and financial constraints – and operational or behavioral (effect-type) barriers related to segregation, storage, and handling practices. The hierarchical ISM model further clarifies how macro-level policy constraints cascade into micro-level operational issues, reinforcing a systems-thinking perspective. This contribution extends CE theory by demonstrating that healthcare waste management operates as an interconnected process flow rather than an isolated environmental task, highlighting the importance of aligning institutional frameworks with operational capabilities to achieve systemic CE transformation.

However, the study has several limitations. The focus on hospitals in Central Java limits the generalizability of the findings to other regions or healthcare systems. Expert-based assessments may introduce subjective bias, and the absence of a quantitative cost-benefit evaluation reduces the economic depth of the recommendations. Moreover, socio-cultural dimensions – particularly public perceptions and trust – were not examined in detail and merit further attention in future research to strengthen the adoption of the circular economy in healthcare waste management.

In addition, the study does not include a sensitivity or stability analysis. Although sensitivity analysis is widely used in many multi-criteria decision-making approaches to test the robustness of results against variations in expert judgments [52, 53], the DEMATEL-ISM method demonstrates inherent robustness. Prior studies indicate that DEMATEL-ISM consistently maintains the exact causal ordering and hierarchical structure even when substantial fluctuations are introduced into expert weightings or influence values [54, 55]. This stability emerges because the method emphasizes identifying fundamental causal patterns and interdependencies rather than relying on precise numerical ratings [56, 57]. As a result, DEMATEL-ISM is less vulnerable to rank-reversal and often yields stable outputs without extensive perturbation testing [58, 59, 60]. This robustness is especially advantageous in complex systems, where subjective expert opinions are indispensable for initial data collection.

Nevertheless, to enhance reproducibility and strengthen methodological rigor, future studies are encouraged to incorporate sensitivity or robustness analysis – particularly when larger expert panels, broader datasets, or hybrid analytical frameworks (such as integrating DEMATEL-ISM with system

dynamics or agent-based modeling) are available. Such extensions would provide deeper verification of the stability of causal and hierarchical structures developed in healthcare waste management systems.

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