Opportunities and challenges for solid waste reuse and recycling in emerging economies: A hybrid analysis

Abstract

This study enriches sustainable solid waste management knowledge by establishing a valid hierarchical model and critiques the causal interrelationship between waste reuse and recycling attributes. The challenges and opportunities for sustainable waste reuse and recycling are emphasized, and direction is provided for practices. Many developing and emerging countries have been attempting to address solid waste management problems and serious restrictions on material reuse and recycling activities. However, it is not well developed, and reuse and recycling efforts have not yet been well implemented due to weak economic and political institution levels. This study aims to propose a sustainable solid waste management model and address opportunities and challenges for waste reuse and recycling in a developing country. A hybrid approach is adopted using a systematic data-driven analysis comprising content analyses, system uncertainty and complexity, the fuzzy Delphi method, interpretive structural modeling, and the fuzzy decision-making trial and evaluation laboratory. The results show that 19 valid indicators are congregated into five aspects, in which circular resource management, societal requirements, and municipal sustainability are causative aspects with the capability to improve sustainable solid waste management as it regards waste reuse and recycling. The top prominent indicators helping to enhance practices are the circular economy, the informal sector, material flow analysis, policy restrictions, waste treatment technologies. The state-of-the-art literature is presented, and further opportunities and challenges are determined.

***Keywords**:* Sustainable solid waste management; reuse and recycling; emerging country; data-driven

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1. Introduction

In recent decades, many developing and emerging countries have been dealing with massive population and economic growth. Such rapid development is also associated with an immense increase in solid waste (Ahangar et al., 2021; Fei et al., 2016; Patwa et al., 2021; Browning et al., 2021). Subsequently, solid waste management (SWM) is generating major problems, causing a downgrading of air, land, and water quality with negative consequences for natural ecosystems and social health (Siddiqi et al., 2020). It is argued that sustainable efforts to diminish solid waste can contribute to major reductions in the amount of generated waste (Yu et al., 2021; Li et al., 2020). Certainly, sustainable solid waste management (SSWM) is an innovative solution for solid waste treatment to improve operational quality and meet the goals of reduction, reuse, and recycling strategies. Realizing waste as an indispensable resource, the material produced through reuse and recycling is argued to offer an efficient resolution to waste management problems (Tsai et al., 2020a). Bui et al. (2020a) claimed that waste should be preserved as a resource to promote resource efficiency, cut carbon emissions, and endorse cleaner and green production activities to reach sustainable development goals. Tsai et al. (2020b) proposed conserving waste as a resource for inputting matter and executing resource recovery to improve efficiency and ecological fortification.

However, emerging countries, in general, have insufficient SWM, with low waste collection ratios, a high rate of waste discard by dumping, and very restricted means for potentially reusing and recycling materials (Florio et al., 2019). Jnr et al. (2018) observed that recycling substructures for waste materials do not routinely exist; accordingly, waste with little or no value ends up in uncontrolled and illegal landfills, having clear negative influences on local societies. Tsai et al. (2020b) stated that SSWM has not been achieved in practice because secondary markets have not seen solid waste as a valuable resource, such as for recycled production and energy recovery. For many developing countries with weak economic and political institution levels, SWM is not well developed, and reuse and recycling efforts have not yet been well implemented (Fei et al., 2016; Ravichandran & Venkatesan, 2021; Batista et al., 2021). This study aims to propose an integrated model of sustainable solid waste reuse and recycling in emerging countries and addressing the challenges and opportunities in which decision makers can sensibly consider as site references and assimilate sustainability.

There are a growing number of studies on SSWM reuse and recycling in developing and emerging countries (Yu et al., 2021; Kheybari et al., 2019; Song et al., 2017; Razzaq et al., 2021). Fei et al. (2016) proposed integrating formal and informal recycling systems into SSWM as an instantly available feature of recyclable household waste. Minunno et al. (2020) and Tsai et al. (2020a) explored circular economy (CE) reimbursements for reuse and recycle practices through a segmented and indicative structure. Kumar et al. (2020) outlined guidance for choosing a factory location for sustainable waste electrical and electronic equipment recycling. Gu et al. (2021) proposed flexible and judicious recycling strategies with the potential to accelerate demographic and economic policies toward zero-waste cities. Araya-Córdova et al. (2021) approached the problem of inequal income and resource allocation efficiency for recycling program adoption by municipalities. The literature recognizes that SSWM consists of essential components such as policy and legal attributes; natural and environmental criteria; socioeconomic factors such as communities, stakeholders, state authorities and financial supports; and waste facility technologies and management practices. Data on these can be extracted and treated as sustainability indicators for both reuse and recycling establishments (Alam et al.; 2019; Yu et al., 2021, Bui et al., 2020a; Kumar et al., 2020).

In general, there is much accumulated SSWM literature on how to steer through the challenges and opportunities for future academic and practical work, but to the best of our knowledge, only a few studies have exploited data-driven analysis to investigate this massive amount of information, identified the indicators and developed a model for sustainable solid waste reuse and recycling. This study offers systematic data-driven delivery of state-of-the-art SSWM for sustainable solid waste reuse and recycling and detects potential challenges and opportunities for future work. Both qualitative and quantitative approaches are included. A hybrid method using content analysis, the fuzzy Delphi method (FDM), interpretive structural modeling (ISM), and the fuzzy decision-making trial and evaluation laboratory (FDEMATEL) has been implemented because the broad study area, diffuse data and diverse system borders may result in uncertainty and complexity for the SSWM system and decision-making challenges (Fei et al., 2016, Ajwani-Ramchandani et al., 2021; Valenzuela-Levi et al., 2021). Content analysis is implemented to identify the SSWM indicators for waste reuse and recycling using publication data from the Scopus database (Tsai et al., 2021a). The FDM is used to validate indicators generated database by using experts' linguistic evaluation (Bui et al., 2020b). ISM is employed to construct a hierarchical model involving indicators with complex relationships (Tseng et al., 2021a;b). The FDEMATEL is utilized to identify the causal interrelationships for the SSWM model and important indicators for future work from qualitative information (Bui et al., 2021b). This study's objectives are presented as follows:

- To generate a valid SSWM indicator set toward waste reuse and recycling from the existing literature
- To identify a SSWM hierarchical model toward waste reuse and recycling.
- To determine causal interrelationships for the SSWM model and important indicators that represent future work challenges and opportunities for developing countries.

This study enriches the literature by contributing to (1) understanding the underlying knowledge of SSWM indicators for sustainable waste reuse and recycling; (2) directing future work by systemizing the SSWM hierarchical model through data-driven analysis; and (3) measuring the causal interrelationships in SSWM and identifying the important indicators for SWM practices in developing countries.

The remainder of this study is presented as follows. The next section presents the literature on SSWM and the sustainable reuse and recycling of solid waste in emerging economies. The proposed methodology is developed in the third section. The fourth section provides the analysis results. The fifth section discusses future trends, challenges and opportunities for SSWM directed toward sustainable waste reuse and recycling. Finally, concluding remarks and suggestions for future work are given in the last section.

2. Literature review

2.1. Sustainable solid waste management

SSWM is a set of SWM activities concerning municipal advancement, wherein resources are sufficient to fulfil demand for daily consumption while guaranteeing ecosystem sustainability by using appropriate waste collection, handling, reuse, recycling and resource conservation (Chang and Pires; 2015). The SSWM concept is an integrated management process encompassing multiple triple bottom line dimensions, including social, environmental, and economic (Florio et al., 2019; Yadav and Karmakar, 2020). Tsai et al. (2021b) argued that SSWM is crucial for all phases of the management process, from design to planning, operation and discharge. Aid et al. (2017) proposed that SSWM not only plays a major role in empowering resource conversion but also possibly generates more occupational and business opportunities by providing a new approach to resource utilization.

In the literature, SSWM execution is one of the most critical steps for municipal development. Yadav and Karmakar (2020) implied that different SSWM technique can be applied to address environmental preservation, societal resolutions, and economic structures. Bui et al. (2021b) confirmed that developing SSWM regulations offers higher operational value through services such as energy recovery, material recycling, and landscape improvements and cleanliness. However, insufficient responses and environmental consequences remain barriers when developing SSWM in practice (Ahangar et al., 2021; Mohammadi et al., 2019). Um et al. (2018) found that an SSWM system is hard to establish due to complex and time-consuming government requirements for planning approval. Aid et al. (2017) found that the ecological influences of discharged solid waste are creating pressure on local authorities to implement suitable tools and policies to resolve the situation. Ikhlayel (2018) stated that barriers to SSWM are inadequate facilities and infrastructure; insubstantial planning strategies; legislative deficiencies; a lack of occupational abilities, knowledge, and informative communication systems; and insufficient funding and sponsorship. These findings reveal that SWM is still far from approaching sustainability targets. Defining the critical indicators for an SSWM approach is important to manage the generated waste, deliver economic benefits, and alleviate the collective problematic status.

The explicit configuration of solid waste varies between geographies and is characteristically linked to the socioeconomic situation. It most comply comprises organic wastes such as food, cardboard, and paper and inorganic wastes such as glass, metals, and plastics (Kheybari et al., 2019; Siddiqi et al., 2020). Some forms of waste could become a potential recyclable or reuse resource, such as various types of paper, cardboard, glass, plastic, tires, textiles, metal, electronics and batteries, or could be composted eco waste, such as garden or food waste. SSWM is an efficient way to treat these materials while reducing their environmental impacts by reducing the use of ordinary resources (Lu et al., 2019). In particular, reused and recyclable waste is fundamental to SSWM and to environmentally friendly resource and material utilization. Bui et al. (2020b) argued that resource competence and reuse and recycling maximization can offer intense reductions to environmental impacts and instigate systemic resource utilization by reducing waste generation, minimizing carbon emission impacts, sanitizing secondary materials, and improving ecological performance. Tsai et al. (2020a) claimed that the SSWM system requires that waste management procedures for reuse and recycling and energy and resource recovery to be cohesive throughout the entire chain of waste transport, disposal, and discard technologies.

However, the SSWM tactic for reuse and recycling is nonsustainable in practice since SWM is currently obstructing economic development and urbanization and negatively driving discrimination and sociocultural concerns, institutional and political issues, and global impressions. Sukholthaman and Sharp (2016) argued that there are barriers to authoritative agreement on engaging in recycling due to the of prospective damage to the environment. Um et al. (2018) indicated that unclear waste management for ordinary products and resolution regarding recycling lead to societal distrust of recycled products. Esmaeilian et al. (2018) implied that SSWM strategies and practical systems have collapsed, although the technical practices are embedded for repurposing, reusing and recycling or for waste-to-energy services. Therefore, SSWM needs to be re-investigated to identify the challenges that drive unsustainability and to attempt to realize sustainable development as a valuable opportunity. Further examination is required for both SWM academics and practitioners to advance performance and accomplish sustainability.

2.2. Sustainable solid waste reuse and recycling:

Resource recycling and material reuse activities have taken place since the commencement of human history and bring many benefits. Recycling is a procedure in which waste materials are converted into new materials, substances and items, while the reuse of waste entails taking any products or product parts and using them again in the original use or for a different function (repurposing or inventive reuse) (Villalba, 2020). The reuse and recyclability of a material relies on its ability to return to its initial form. Reuse and recycling offer advantages because they reduce mineral and energy consumption, reduce pollution and greenhouse gas emissions, and reduce solid waste disposal and landfills. Martin et al. (2017) suggested that these activities substitute raw material involvement and remove waste out of the economy with the aim of a sustainable environment. Thus, waste that it potentially useful is utilized, and new material consumption is reduced, thereby saving energy and reducing pollution, such as from incineration and landfilling (EU Directive, 2012).

Solid waste generation can be considered an opportunity for renewable energy generation, new employment and economic advantages as well as for improving community awareness about ecological problems (Ferronato & Torretta, 2019). Nevertheless, the growth of waste continues to require suitable dispensation, stowage, and recycling through innovative solutions to meet demand (Kheybari et al., 2019; Yu et al., 2021). Siddiqi et al. (2020) argued that the major problem affecting recycling and recovery is that most efforts concentrate downstream of the waste management process. Yu et al. (2021) proposed a complete understanding of 4R development (reduce, reuse, recycle, and recover) and lessening the total amount of waste while diversifying any remaining waste for reuse or recycling. However, authorities' ability to supervise waste is inadequate, resulting in unproductive and deficient waste management in practice (Naldi et al., 2021, Batista et al., 2021). For example, Kihl and Aid (2016) found that legislation on sorting recyclable waste material results in costly, time-consuming and intricate governmental consent procedures that paradoxically obstruct waste material reuse. Tsai et al. (2020b) stated that collaborating with private servicers may increase embezzlement and corruption in municipal finances and that the requirements conceived for solid waste and its reutilized objects are undistinguishable and may lead to social distrust of recycled products. Furthermore, Bui et al. (2020b) claimed that improper waste sorting makes recycling more complex, while imported technologies are not productive. Gaps remain in defining solutions to refurnish resources and prevent negative effects for sustainable solid waste reuse and recycling, and these require more advanced research and application.

2.3. Sustainable reuse and recycling of solid waste in emerging economies

Emerging economies are endeavoring to transform themselves into progressive economies via augmented production, governance forms and conservation, and progressively conversant marketplaces (Bao & Lu, 2020; Li et al., 2020). Emerging economies are generally experiencing a transition from a less developed, low-income and preindustrial country to an industrialized and modern economy with advanced living specifications. However, the struggle between economic development and environmental degradation is notable (Zhao et al., 2019; Yang et al., 2019). Emerging countries, such as China, India, and Brazil, have seen the immense expansion of economic activities and population growth generate vast amounts of solid waste that must be managed (Bao & Lu, 2020). Many of these countries seek an advanced SSWM system that aligns with better sorting of source materials and high recycling proportions, but they lack adequate SWM capability to balance their sustainable development goals (Browning et al., 2021; Fei et al., 2016).

Resources must be preserved, reused and recycled, not discarded. Since emerging economies are on the path to industrialization and joining the global community, establishing resource reuse and recycling is important for developing nations. However, many of them are unable to handling the waste they produce due to numerous restrictions. Diaz-Barriga-Fernandez (2017) defined a number of likely problems in developing countries that stop them from achieving reuse and recycling objectives, such as a lack of political determination and national policy associated with SWM, the absence of local regulations and instructions, inadequate funding, a severe lack of training and education at all levels, and the lack of a legislative framework for preserving or establishing a CE. Schreck & Wagner (2017) stated that many bodies propose many SWM programs, but that too much generated waste is landfilled, meaning that policy initiatives over the years in many countries have been inadequate. Tsai et al. (2020b) claimed that insufficient standards for choosing technologies; planning, constructing and operating solid waste handling facilities; and investing in waste assembly and transport paraphernalia have instigated ineffective and inaesthetic enactment of the sustainable reuse and recycling of solid waste. Siddiqi et al. (2020) specified that safe waste collection, treatment, and disposal systems are rare in developing countries, as these systems and procedures are cost-centric and coincide with imperceptible or fictional environmental policies. Browning et al. (2021) declared that mismanaged and unmanaged waste is a severe issue in developing countries, where the facilities for sorting, reuse and recycling is often inadequate or missing.

Many developing countries have informed solutions for cultivating sustainable reuse and recycling, such as waste repurchase projects, biogas or compost production, waste-to-energy technology implementations, the reutilization of glass and metals, supplementary manufacturing, waste pickers and authorized industry integration (Sawadogo et al., 2018; Ghisolfi et al., 2017). In particular, electric and electronic equipment waste management, char fuel production, battery recycling, atmospheric pollution, informal sector inclusion, SWM risk taking, healthcare waste management, and household hazardous waste management have received increasing attention (Kumar et al., 2020; Araya-Córdova et al., 2021; Siddiqi et al., 2020; Gu et al., 2021). Fei et al. (2016) studied the cash flows, material flows and recycling paths in an informal recycling system within Suzhou's SWM in China and suggested targeted policy in a pressure-state-response framework. Pardo Martínez & Piña (2017) studied external requirements for the informal sector regarding formal alliances, recycler recognition and the price stabilization of recycling resources in Bogotá (Colombia). Valenzuela-Levi (2020) compared municipal SWM in Medellín in Colombia to that in Santiago, Chile, arguing that political settlements create recycling income through both institutional-formal sectors and informal stakeholders, including tolerance for scavenging and diminishing civic resolution due to debasement. Ajwani-Ramchandani et al. (2021) focused on corporations and the coordination of diverse incentives to drive stakeholders toward CE in India to improve social, environmental, and economic consciousness. Yu et al. (2021) proposed environmental planning through automatic operation via artificial intelligence for reduction, reuse, recycling and recovery to optimize the waste management procedure. Mairizal et al. (2021) provided a valuation and forecast of electronic waste generation and its recoverable metallic value to build a possible distribution plan for recycling systems in Indonesia. Valenzuela-Levi et al. (2021) stipulated an innovative optimization process for material redistribution to promote recycling adoption among suppliers and recycling policy implementation in the complex political and institutional environment of Santiago.

However, barriers still remain to waste reuse and recycling improvement in developing countries. Fei et al. (2016) reported that the SSWM strategy was in its early stages, although lively informal sectors collected, dispensed and transacted recyclable materials, while formal SWM businesses were launching trial frameworks for assorted recyclables. Jambeck et al. (2018) and Pani & Pathak (2021) stated that systemic poverty and environmental injustice can be accredited to the absence of infrastructure and the inequitable provision of economic resources resulting from waste disposal, as well as a lack of accountability and an operating political capacity for governance. Ferronato et al. (2019) argued that traditional SWM infrastructure is often obstructed by natural hazards and political uncertainty, while most countries have difficulty delivering the facilities required for the safe and appropriate maintenance, creation, and supervision of SSWM. Araya-Córdova et al. (2021) proposed that the governments in most developing countries have no national SWM strategy, while recycling projects are a self-governing initiative supported by localities. Therefore, empowering society in limited areas of infrastructure to take charge of SWM while ensuring sustainable benefits is difficult, especially given the enormous quantities of waste as an outcome of massive industrial and economic development, population expansion, and lifestyle changes (Ikhlayel, 2018; Patwa et al., 2021; Song et al., 2017). Such movements must be tacit in many developing and emerging countries, as they aim to balance development and sustainable growth, and more solutions need to be tested and implemented using appropriate SSWM patterns.

Developing successful SSWM nationwide depends on high support, time and money, which developing countries lack. While there are efforts to address SSWM, the reuse and recycling of waste raises interest among researchers who aim to gauge the many opportunities and challenges in the future. Hence, the emphasis on particular indicators in the literature is critical to determining the failure or success of SSWM. This study aims to propose a theoretical model that focuses on sustainable solid waste reuse and recycling and identify opportunities and challenges for emerging economies in practice.

3. Method

3.1. Proposed method and analytical steps

Previous studies have adopted many methods to measure waste reuse and recycling for SSWM. Jnr et al. (2018) used an optimization technique to provide direction for a low-density polyethylene production process at the workroom scale and verified the key parameters for improving production performance. Kumar et al. (2020) established a sustainable position framework for electrical and electronic equipment waste recycling plants in emerging economies using the best-worst method and VIsekriterijumska optimizacija i KOmpromisno Resenje (VIKOR). Minunno et al. (2020) applied a methodology based on a systematic literature review and life cycle assessment to explore environmental assistance for reuse and recycle implementation in a CE. Valenzuela-Levi et al. (2021) formulated an optimization model based on two political options for redistributing and increasing existing resources and promoting recycling adoption for municipal SSWM. Yu et al. (2021) proposed automated waste reuse and recycling planning using artificial intelligence and established a hybridized intelligent framework to optimize the waste management process. However, SSWM requires high involvement due to its extensive scale, complex practices, uncertainties encountered in the real world and multidimensional attributes (Araya-Córdova et al., 2021). A novel holistic method that encompasses both qualitative and quantitative approaches is required. This study extrapolates a systematic data-driven approach to distribute state-of-the-art SSWM in solid waste reuse and recycling implementation and detect potential challenges and opportunities for future work. A hybrid method is executed using content analyses, FDM, ISM, and FDEMATEL (Fei et al., 2016, Ajwani-Ramchandani et al., 2021; Valenzuela-Levi et al., 2021).

Content analysis is applied in this study to detect the SSWM indicators for waste reuse and recycling using the Scopus publication database. The data-driven analysis includes content analysis to exploit data and sort information (Tsai et al., 2021b). This technique offers the systematic reading or generation of artifacts or texts by scanning documents and letter objects, and it also allows the study of publication distribution. Bhatt et al. (2020) developed a sustainable manufacturing knowledge construct using content analysis. Bui et al. (2021) utilized the technique to illustrate and mold a SSWM conceptual framework that captured the divergence of contemporary literature. Content analysis is a critical stage in research, as it measures a high information volume through systematic and constructed tactics by specifically seizing textual data through text mining and constructively categorizing the relevant data.

However, the original indicators generated still must be clarified and validated. FDM is then applied to validate these indicators based on the linguistic judgment of experts (Bui et al., 2020a Tseng and Bui, 2017). In particular, fuzzy set theory is adopted using the traditional Delphi method to obtain quantitative values from high-uncertainty linguistic preferences while still maintaining the qualitative features. Tseng and Bui (2017) used the FDM to improve the validity and reliability of analysis outcomes and minimized uncertain expert judgment while scrutinizing the strength of attributes. Tsai et al. (2021a) applied the FDM to address the uncertainty of experts, increase questionnaire accuracy and ensure analysis quality. This method involves group decision-making, deliberate choices by eliminating or emphasizing experts' or decision makers' opinions and reduced decision time.

Subsequently, the extended ISM and FDEMATEL is used. ISM arranges indicators into a systematic hierarchical model by grouping indicators based on complex relationships (Tsai et al., 2020b; Tseng et al., 2021a). The method tackles issues with attribute interdependence by combining computational, theoretical, and conceptual compensation into a multifaceted outline of logical correlations among the attributes; then, it provides a basic graphic to define the direction of the attributes system. The method handles the complexity of experts' linguistic preferences and hierarchy modeling by offering predetermined information for the strategic direction of attribute interdependence. Yet, the hidden causal interrelationship among the attribute have not yet been clarified. Formally, FDEMATEL is employed to clarify the causal interrelationship for the SSWM model and indicate important indicators for future work. The method defines the causal interrelationships among the attributes using qualitative material from the linguistic descriptions of experts to create a causal diagram (Tseng et al., 2021a). Fuzzy set theory is utilized to quantify experts' ambiguous judgments regarding the nature of uncertainty into crisp values, and the DEMATEL technique is used to analyze the interrelationships between aspects and indicators. Bui et al. (2021) used this method to measure the causal interrelationship among attributes and indicate the critical attributes requiring enhancement. Tseng et al. (2021a;b) employed a hybrid ISM and DEMATEL to construct a causal hierarchical model and thereby addressed multicriteria decision-making uncertainty and complexity. From the above discussion, the proposed methods are identified as suitable for this study to assess SSWM.

The analysis steps are suggested as follows (shown in Figure 1):

1. Proper search terms are chosen to apply content analysis with the aim of collecting information from the database. The keywords are generated and confirmed by the authors using a group discussion as input for the FDM.
2. The FDM is applied to refine keywords into valid SSWM indicators for waste reuse and recycling. A questionnaire is created and delivered to the experts to collect their evaluations.
3. The contextual structure is critiqued using an indicator set resulting from the FDM. Using the ISM, the hierarchical model is constructed, indicators are grouped into aspects, and the hierarchical digraph is visualized.
4. The hierarchical model is formerly used to accumulate qualitative decisions from experts. FDEMATEL is used to compute the causal interrelationships among attributes and map an illustration of the cause-and-effect for SSWM attributes.

(INSERT Figure 1 HERE)

3.2. Data collection

Prior studies have considered data-driven SSWM by retaining big data from Proquest, JSTOR Archival Journals, Dialnet Plus, ScienceDirect, and Web of Science; however, these databases cover fewer publications. This study selects Scopus because it covers a wide range of publications compared to others and provides numerous identifiers, such as title, abstract, author keywords, author, author affiliation, citation archive, and publication date (Tsai et al., 2020a). There are two coding types in content analysis: deductive and inductive. Deductive coding takes the search term after the data-driven process and identifies central systematic groupings based on the study objectives, while inductive coding searches for analytic groupings from the generated data throughout the analytical procedure. This study uses deductive coding based on the predefined search terms used to identify the SSCM literature on waste reuse and recycling in emerging countries from the Scopus database. The search terms are “("solid waste" and "sustain*") and ("reus*" or "recycl*") and ("emerging countr*" or "developing countr*" or "emerging econom*" or "developing econom*")” and are restricted to titles, abstracts, and keywords.

Next, a committee of 30 experts, with an average of 10 years of experience studying and working in the SWM, reuse and recycling field in emerging and developing countries, is approached for the empirical assessment stage, including 6 experts from related government divisions, 14 experts from academic institutions, and 10 experts in practice at SWM firms (shown in Appendix A).

3.3. Fuzzy Delphi method

In FDM, linguistic terms are utilized to present experts’ evaluations and then are converted into triangular fuzzy numbers (TFNs) (shown in Table 1).

(INSERT Table 1 HERE)

The value of indicator e is measured by expert f as $j_{ef} = \left(n_{ef}; o_{ef}; p_{ef}\right)$, where
$e = 1,2,3, \dots, n$;
$f = 1,2,3, \dots, m$;
n, o, p refer to TFNs implemented from the linguistic scale
n_{ef}, o_{ef}, p_{ef}: refer to the TFNs of indicator e assessed by expert$f$

Then, weight j_e of indicator e is $j_e = (n_e; o_e; p_e)$, where
$n_e = min\left(n_{ef}\right)$;
$o_e = \left(\prod_1^m o_{ef}\right)^{1/m}$; (m: the number of experts)
$p_e = max\left(p_{ef}\right)$,

The convex combination value S_x is acquired through the following equation:

$$S_e = \int(l_e, u_e) = \gamma[l_e + (1 - \varepsilon)u_e] \quad (1)$$

in which

$$l_e = p_e - \gamma(p_e - o_e) \quad (2)$$

$$u_e = n_e - \gamma(o_e - n_e) \quad (3)$$

where γ addresses the decision-makers’ optimism level and achieves balanced evaluations among experts. $\gamma = [0.1]$ shows whether experts are positive or negative in their perception. This value is generally assigned as 0.5 in common contexts.

Ultimately, a threshold for eliminating invalid attributes is applied using the following equation:

$$\mu = \sum_{e=1}^{n}(S_e/n) \qquad \text{where } n \text{ refers to the number of indicators} \quad (4)$$

If $S_e \geq \mu$, indicator e is accepted; otherwise, the indicator must be removed.

3.4. Interpretive structural modeling

Four characteristics are used to clarify the influence between two indicators (i and j):

V: indicator i influences indicator j, but the influence is not in the other direction. (5)

A: indicator j influences indicator i, but the influence is not in the other direction. (6)

X: indicators i and j influence each other. (7)

O: no relationship exists between i and j. (8)

These characteristics establish a structural interaction matrix explaining experts' linguistic evaluations, which is then transformed into binary code by substituting directions to acquire a reachability matrix. The deputization of the reachability matrix is addressed using the following equation:

$$[(g,y),(g,y)] \rightarrow V = (1,0); A = (0,1); X = (1,1); O = (0,0). \tag{9}$$

The reachability and antecedent sets are determined to assemble a total reachability matrix from the individual reachability matrices. Here, $T^a = \left[t_{ij}\right]_{n\times m}$ exemplifies the a^{th} expert's individual reachability matrix; hence, the total reachability matrix T^T is calculated using the following equation:

$$T^T = \frac{1}{x}\left(t_{ij}^1 + t_{ij}^2 + \cdots + t_{ij}^a\right), i,j = 1,2,3,\ldots,n. \tag{10}$$

When $T^T > 0.5$, the assembled influence is considered to be 1; otherwise, it is 0.

Next, the reachability (T') and antecedent (R') set are derived from the total reachability matrix using the following equation:

$$t_i = 1, T' = \left\{t_1^{T'}, t_2^{T'}, \ldots, t_n^{T'}\right\};\ t_j = 1, R' = \left\{t_1^{R'}, t_2^{R'}, \ldots, t_n^{R'}\right\}. \tag{11}$$

Accordingly, the intersection set S' is generated using the following equation:

$$S' = T' \cap R'. \tag{12}$$

The intersection set results from concurring indicators, and the indicators with higher values are assigned in levels as an ISM hierarchy. The indicators at one hierarchy level cannot enable indicators to reach the other levels. After the upper level is established, the utilized indicators are removed from the other levels. This process is replicated until all the indicators have been assigned.

3.5. Fuzzy decision-making trial and evaluation laboratory

The FDEMATEL linguistic scales shown in Table 2 are implemented for the assessments. If there are a experts, they are asked to evaluate the interrelationships between the b^{th} and c^{th} attributes, as E_{bc}^a. Then, these linguistic assessments are transformed into corresponding TFNs as $\left(e_{\ell}{}_{bc}^{a}, e_{m}{}_{bc}^{a}, e_{r}{}_{bc}^{a}\right)$.

(INSERT Table 2 HERE)

The normalization procedure is implied for the defuzzification as follows:

$$\bar{E}_{bc}^a = \left(\bar{e}_{\ell}{}_{bc}^{a}, \bar{e}_{m}{}_{bc}^{a}, \bar{e}_{r}{}_{bc}^{a}\right) = \left[\frac{\left(\bar{e}_{\ell}{}_{bc}^{a} - min\,\bar{e}_{\ell}{}_{bc}^{a}\right)}{\tau}, \frac{\left(\bar{e}_{m}{}_{bc}^{a} - min\,\bar{e}_{m}{}_{bc}^{a}\right)}{\tau}, \frac{\left(\bar{e}_{r}{}_{bc}^{a} - min\,\bar{e}_{r}{}_{bc}^{a}\right)}{\tau}\right] \tag{13}$$

where $\tau = max\,\bar{e}_{r}{}_{bc}^{a} - min\,\bar{e}_{\ell}{}_{bc}^{a}$

Then, the left ($\mathrm{L}_{\mathrm{bc}}^{\mathrm{a}}$) and right ($\mathrm{R}_{\mathrm{bc}}^{\mathrm{a}}$) normalized values are obtained using the following equations:

$$\left(L_{bc}^a, R_{bc}^a\right) = \left[\frac{\bar{e}_{m}{}_{bc}^{a}}{\left(1+\bar{e}_{m}{}_{bc}^{a} - \bar{e}_{\ell}{}_{bc}^{a}\right)}, \frac{\bar{e}_{r}{}_{bc}^{a}}{\left(1+\bar{e}_{r}{}_{bc}^{a} - \bar{e}_{m}{}_{bc}^{a}\right)}\right] \tag{14}$$

The crisp value (CP_{bc}^{a}) is calculated as follows:

$$CP_{bc}^{a} = \frac{[L_{bc}^{a}(1-L_{bc}^{a})+(R_{bc}^{a})\times(R_{bc}^{a})]}{(1-L_{bc}^{a}+R_{bc}^{a})} \quad (15)$$

Next, the total crisp values are arranged into a direct relation matrix $[DR]$ by accumulating all experts' crisp values using the following equations.

$$dr_{bc} = \frac{\sum_{a=1}^{f} CP_{bc}^{a}}{a}, b, c = 1,2, d \quad (16)$$

$$[DR] = [dr_{bc}]_{d\times d} \quad (17)$$

The following equations are used to normalize the direct relation matrix $[\overline{DR}]$:

$$[\overline{DR}] = \left[\frac{dr_{bc}}{\max\limits_{1\leq b\leq d} \sum_{c=1}^{d} dr_{bc}}\right]_{d\times d} \quad (18)$$

The total relations matrix $[TR]$ is obtained as follows:

$$[TR] = [\overline{DR}] \times \{1 - [\overline{DR}]\}^{-1} \quad (19)$$

Then, $[TR]$ is articulated as $[tr_{bc}]_{d\times d}$.

From the total relation matrix, the driving power (α) and dependence power (β) are obtained as follows:

$$\alpha_i = \sum_{b=1}^{d} [tr_{bc}]_{d\times d} = [tr_b]_{d\times 1} \quad (20)$$

$$\beta_i = \sum_{c=1}^{d} [tr_{bc}]_{d\times d} = [tr_c]_{1\times d} \quad (21)$$

Finally, the aspects are mapped into cause-and-effect graphics devised from the integration of $[(\alpha_i + \beta_i), (\alpha_i - \beta_i)]$. $(\alpha_i + \beta_i)$ is attribute i's importance level, and $(\alpha_i - \beta_i)$ categorizes attributes into cause or effect groups by identifying $(\alpha_i - \beta_i) > 0$ and $(\alpha_i - \beta_i) < 0$, respectively.

4. Results

4.1. Data collection

The data generated from Scopus show a total of 214 publications for the articles and reviews in the English language for the content analysis. Author keywords are identified for co-occurrence coupling using VOSviewer software, and there are 117 keywords that occur at least 2 times. After removing all the repetitions, synonyms, acronyms, industrial and methodological keywords, 54 keywords remained as FDM inputs (see Appendix B).

4.2. Fuzzy Delphi method

Fifty-four keywords are proposed for the FDM assessment. The weight and the threshold for refining the indicators are obtained. The experts' judgments of the linguistic terms are converted into corresponding TFNs (see Table 1). The FDM is utilized to filter the valid indicators, which are acquired (see Appendix C) based on the threshold of $\mu = 0.292$. Nineteen indicators are accepted as SSWM indicators and proposed for the next analytical step (see Table 3).

(INSERT Table 3 HERE)

4.3. ISM

The contextual relationship matrix is next obtained (see Table 4). The relationships between indicators are illustrated by means of 4 characters. This qualitative information is transformed into quantitative binary code data by switching directions (see Table 5). The table consists of supporting areas, with the inverse zones identified by the diagonal. Below the diagonal represents the influence from indicator i to indicator j; in contrast, above the diagonal refers to the influence from indicator j to indicator i.

The intersection set is displayed according to the reachability and antecedent matrices (see Table 6). The 19 indicators are set into eight levels grouped into 5 aspects (see Figure 2) capable of improving SSWM for waste reuse and recycling (see Figure 3). The aspects comprise circular resource management (A1), societal requirements (A2), waste features (A3), waste management facilities (A4), and municipal sustainability (A5) (see Table 7).

(INSERT Table 4 here)

(INSERT Table 5 here)

(INSERT Table 6 here)

(INSERT Table 7 here)

(INSERT Figure 2 here)

(INSERT Figure 3 here)

4.4. Fuzzy DEMATEL

From the ISM hierarchical framework, the expert committee judges the aspects' interrelationships via the provided linguistic scales (see Table 2). The fuzzy direct relation matrix and the defuzzification are provided (see Appendix D). The initial direction matrix is generated by averaging the crisp value of all experts (see Table 8). The total interrelationship matrix is computed to identify the causal interrelationships among aspects (see Table 9). Accordingly, the cause-and-effect diagram is revealed via the $(\alpha + \beta)$ and $(\alpha - \beta)$ axes (see Figure 4). Societal requirements (A1), circular resource management (A2), and municipal sustainability (A3) are identified as the causal aspects of the system, and waste features (A4) and waste management facilities (A5) are assigned as the affected aspects.

Circular resource management (A2) shows the strongest and most important aspects of SSWM that are related and that have potential driving effects. The aspect strongly effects on the waste features (A4) and waste management facilities (A5), and had medium effects on societal requirements (A1) and municipal sustainability (A3). The results show that societal requirements (A1) and municipal sustainability (A3) have weak and medium effects on the other aspects, respectively. In particular, societal requirements (A1) unexpectedly shows reverse effects on (A2) (see Figure 4).

(INSERT Table 8 here)

(INSERT Table 9 here)

(INSERT Figure 4 here)

Likewise, the indicators' initial direction matrix and total interrelationship matrix are provided (see Tables 10-11). The cause-and-effect interrelationships among the indicators are obtained in Table 12. Then, the cause-and-effect diagram is generated (see Figure 5). For the indicators, this study employs the average value of $(\alpha+\beta)$ to categorize and divide the diagram into four quadrants. $(\alpha+\beta)$ denotes the indicators' importance value: the greater the $(\alpha+\beta)$ value is, the more important the indicator and the higher its level (Bui et al., 2021). The most important indicators are identified as CE (I1), the informal sector (I6), material flow analysis (I8), policy restrictions (I9), and waste treatment technologies (I16). These indicators are the subject of focus, since by improving these indicators, the others can also be improved.

(INSERT Table 10 here)

(INSERT Table 11 here)

(INSERT Table 12 here)

(INSERT Figure 5 here)

5. Discussion

5.1. Theoretical implications

SSWM must conduct waste treatment processes and leverage the connections between numerous products considering sustainability dimensions. However, environmental threats, unsatisfactory social prospects, and economic disputes have resulted in challenges to the momentum achieved among scholars, policymakers, and practitioners (Martin et al., 2017, Ajwani-Ramchandani et al., 2021). SSWM facilities are simply not implemented because the required principles are not representative; enumerating and evaluating boundaries must reflect system uncertainty (Bui et al., 2020b). This study identified the causal SSWM aspects of circular resource management, societal requirements, and municipal sustainability as the focal aspects to improve waste reuse and recycling performance.

5.1.1. Circular resource management

Circular resource management is the strongest and most important aspect of the SSWM system directed toward waste reuse and recycling. Fluctuating consumption behavior results in supply uncertainty, resulting in rare earth resource scarcity or geopolitical restrictions and creating political problems that obstruct the supply chain (Kumar et al., 2020). This challenges resource distribution in recycling adoption. Prior studies have presented the inequality issues in SSWM, reuse and recycling; however, they have not looked at the necessary elements that clarify inequality and tackle the reuse and recycling processes (Araya-Córdova et al., 2021). Circular resource management, which emphasizes achieving a regional or local CE, is one of these. This aspect helps to reduce environmental influence by reducing new raw material usage, encouraging waste prevention, inspiring the use of secondary and environmentally friendly materials, and promoting renewable energy consumption (European Commission, 2021). This presents opportunities for a structural transition to effective resource management relying on circularity principles consisting of forming new intuitions in resource absorbing cities, brokering events and monitoring development. However, undertaking circular resource management is difficult due to resource capabilities and economic constraints. Local decentralized CE management employing suitable technological principles to utilize accessible local resources and materials for production for that locality is required (Browning et al., 2021).

The problem is the prejudicial distribution of resources, and SWM charges reparations for the poor, which are likely to be substantial in some cities (Valenzuela-Levi et al., 2021). On the one hand, this requires more comprehensive resource interchange mapping along supply chains, as well as more investigation of ecological influences and value creation by production and businesses (Ajwani-Ramchandani et al., 2021; Song et al., 2017). For structured and efficient procedural occupations, for example, waste transport and material diffusion, logistics networks must be coordinated, as they intensify recycling activities and bring more economic benefits (Karimi et al., 2018, Kumar et al., 2020). On the other hand, there are nonstandard recycling processes in the informal sector, which may cause serious resource waste and environmental pollution. Since recyclable resources bring fiscal value and there are low-income citizens in developing countries, they can gain benefits from buying and reselling waste, implementing an illegal recycling process that makes resource circularity disordered and spontaneous due to the lack of legal awareness and professional knowledge. The question of how to indicate the best solution to apply to this particular aspect in developing countries remains outstanding.

5.1.2. Societal requirement

The societal requirement aspect plays an imperative role in the construction and operational strategies of recycling projects by helping to increase the reuse and recycling levels and endorse waste sorting at the source. For instance, public sentiment and satisfaction are the decisive constituents of the founding and future growth of recycling (Kheybari et al., 2019). Local authorities also offer provisions for land acquisition by recycling firms and financial funding in the form of tax and tariff grants, as well as infrastructure construction (Kumar et al., 2020; Batista et al., 2021). This helps in executing emission reduction policies and improves the overall environmental and social presentation of the firm. There are bulky, varied, and obvious systems with plentiful components, such as waste treatment technologies and social and economic transformations, required to experience an appropriate SWM program (Florio et al., 2019; Yu et al., 2021). The societal requirements highlight zero-waste innovation to endorse the CE, and sustainable social development may help shift from a solely disposal focus to reuse and recycle considerations (Gu et al., 2021). This aspect is often promoted by fervent ecologists and conservationists and organized by hundreds of thousands of volunteers heading community awareness projects, cleanup initiatives, fundraising for waste management campaigns, fascinating viral media posts, etc. This generates social pressure and inspires change among societies (Sharma et al., 2020; Pani & Pathak, 2021).

However, challenges exist, such as reliable information assessment, SSWM knowledge, and data on leftover materials, reuse and recycling, waste treatment and disposal (Bui et al., 2020b). Active social communication systems may be required to distribute and allocate the needed information or seminars/trainings among SWM stakeholders such as private institutions, government agencies, and homeowners. Additionally, images of plastic waste destroying exquisite species, waste being found inside animals' bodies, the destruction of fragile plant life and wildlife, dirty beaches, and gigantic mountains of waste have significantly affected communities; however, poor public acceptability will impede the execution of SSWM projects, especially for reuse and recycling planning (Ajwani-Ramchandani et al., 2021; Sukholthaman and Sharp, 2016). Severe societal and health tribulations also exist. Informal recycling has conventionally been performed by marginal groups and outcasts in developing countries, as it is operated by the social subdivision identified as informal scavengers, who are residents with no/low income, to lever such activities as waste material collection both discretely across the city or intensely at dumpsites (Fei et al., 2016).

Therefore, societal awareness and evolution are argued to be an energetic driver of transformation, for example, of waste handling and the disposition of human rights in SWM activities. Activists, nongovernmental organizations, and resident associations require businesses and government institutions to act to address SWM issue. Partnerships among local recycling firms and manufacturing suppliers may help to reduce the amounts of waste and operational costs and promote mutual benefits. Noteworthy policy improvements in SSWM should be made in advance to address the increasing petitions for renewable materials and the ecological indications and societal influences for eliminating conventional throw-away consumption (Silva et al., 2017; Kumar et al., 2020; Naldi et al., 2021). Aside from political aims to restructure traditional SWM models, those who primarily reframe and reconceptualize the models should also be noticed. When shifting the community's ordinary behaviors towards a positive environmental intention, public education about the reuse and recycling of materials and consumption issues needs to be emphasized (Bui et al., 2020a). All of these factors still need more in-depth measurement and contributions.

5.1.3. Municipal sustainability

Municipal sustainability refers to integrated communal sustainability, an inclusive and collaborative municipal planning process that allows communities to envisage what they want in their future. An assortment of recycling sites may advantageous for municipalities with well-furnished and trustworthy infrastructure in terms of resource availability, logistics facilities, a skilled workforce, accessible gathering centers, and nearby energy sources, as these are critical technical issues that enhance the economic probability of reuse and recycling activities (Kumar et al., 2020; Esmaeilian et al., 2018). In contrast, municipal sustainability is contingent upon a unified recycling program instigating institutional, environmental, and economic perspectives (Araya-Córdova et al., 2021; Ikhlayel; 2018). As a result, important aspects are required to integrate sustainable ecosystems (Pani & Pathak, 2021). Municipal ecotechnological indicators such as road and rail networks, municipal areas, transmission networks, waste supply and disposal facilities, and land use can be established as waste alteration accommodations to support sustainable access to socioeconomic SWM practices, climatic prerequisites, and environmental and geological issues.

Municipal SSWM depends strongly on issues such as urban zones, populations, local budgets, and monetary systems to shorten the recycling achievement gap (Valenzuela-Levi et al, 2021). In particular, reuse and recycling challenges tend to reflect problems such as recycling waste container distribution, inappropriate treatment, and ease of waste transportation networks throughout the city. Therefore, potential suggestions for leveraging waste recyclability are needed. Technological solutions can help to overcome these problems. For instance, the Internet of Things plays an important role in keeping municipalities industrious, healthier, and green (Ahangar et al., 2021; Yu et al., 2021). Smart device connections, carriages, and infrastructure within a city can help recover quality and safe SSWM. Digital data could be used to forecast how a new campaign could grow, thus fostering the SWM workload. However, the municipalities imitating SSWM are physically fragmented. In fact, a reuse and recycling program often develops as a self-governing initiative for SSWM depending on the available municipal financial resources, which tightly relate to resident income in each area. Although recycling adoption by cities is slightly increasing, it is not sufficient for an extensive transformation into an SSWM model. Many people in developing countries are still living in infrastructure-deficient areas with no option but to burn waste, including plastic (Browning et al., 2021). This destructive routine discharges many kinds of toxic emissions into the environment, decreasing human wellbeing.

5.2. Practical implications

Emerging and developing countries are now more concerned about developing the standards and capabilities for SSWM, and reusing and recycling practices are significantly rising among municipal authorities, businesses, and the public (Patwa et al., 2021). Many practices are engrained in operations, but after launch, they are often hard to amend (Ajwani-Ramchandani et al., 2021). The most important indicators identified to improve practical performance are CE, the informal sector, material flow analysis, policy restrictions, and waste treatment technologies.

The CE is one of the main sustainability concepts, as products can be reused, repaired, refurnished or utilized as part of a recycled system, bringing additional social and ecological benefits (Martin et al., 2017). The waste sector, as an integrated part of sustainable development, requires a better understanding of the concepts of CE and sustainable production and consumption (Silva et al., 2017). In particular, reuse and recycling processes are key solutions to improving the CE, as they solve both resource conservation and pollution problems by reutilizing waste (Li et al., 2020). With the principle of reducing, reusing and recycling, CE aims to interpret the conventional manner of resource-product pollution as a sustainable resource-product-renewable approach. However, in the context of developing countries, few studies have approached the reuse and recycling activities for CE concepts and the different ecological affects, such as material reductions, technology implementations, and obstacles to the environmental system (Minunno et al., 2020). In particular, the lack of reuse product marketability and recyclable material competitiveness for the CE on the societal dimension are intrinsic to its missing relevance and sustainable development. The CE requires the sensible optimization of and coordination along the whole value chain, and the potential of digital technologies for sustainably comprehending massive amounts of information to help decisionmakers to make accurate, effective decisions, as well as to manage material and data flows, needs more consideration. It is argued that advanced technologies such as artificial intelligence, blockchain, big data, robotics, and the Internet of Things will help close loops and empower the removal of existing linear production lines. Additionally, political impediments endure challenges through the strong influence of lobbyist clusters, hindering policy regarding SSWM externalities. As only a few regions and cities have established an operational approach for the CE transition, making experience and knowledge available for roadmaps and enabling SSWM through practical reuse and recycling is important.

In developing countries, the absence of funding in rapidly growing municipalities results in a large informal waste sector. Approximately 1 percent of municipal inhabitants, at a minimum of 15 million people, live by picking, transporting, trading and salvaging recyclable waste all over the world (World Bank, 2021). These salvagers are typically from poor, vulnerable, disadvantaged, and downgraded communities, and informal waste recycling is a general method to gain more income. When supported and organized, the sector is able to attract ordinary investment, generate jobs, save cities money, advance business competitiveness, diminish material shortages, preserve natural resources, and shelter the environment. Thus, an SSWM ecosystem requires integrating this significant indicator to form a new model. However, the sector is instigated exclusively through financial provision from governments and is not acknowledged by the community as offering a valuable service, although it is the foremost contributor to a high recycling percentage in many developing countries, such as India, China, and Brazil (Fei et al., 2016). Examination and political propositions are needed, and governments and media need to strengthen associated laws and regulations, change attitudes and recognize the informal sector's contribution. Furthermore, formalizing the appearance of informal workers, encouraging a healthier association among the public, encouraging self-esteem, establishing self-confidence among informal workforces, establishing specialized informal recycling, improving sector integration in SSWM, and fostering collaboration between formal and informal waste management remain unresolved concerns (Aid et al., 2017). It is difficult for authorities to pursue suitable solutions to encourage informal system standardization due to data source diffusion, diverse recycling boundaries and waste treatment techniques, resulting in uncertainty and unspecified conditions. To measure industrial and economic sanitation to improve informal sector wellbeing, adequate funding is needed to renovate informal waste management systems, but it is currently lacking. Additionally, waste picking in its current stage is inadequate to manage the waste crisis. Unpolished approaches with insufficient conservation activities may generate secondary contaminants and diverse poisonous substances and exposure levels in air, soil, and water. Thus, adequate funding must also be provided, equipment offered, and training established on professional recycling knowledge, standardized classifications and processing methods within the sector.

The challenges and opportunities for waste reuse and recycling require superior investment and innovative solutions for sustainable material management. Material flow analysis development for green and cohesive SSWM requires optimum practices to benefit the system (Villalba, 2020). Material flows and resource distribution are essential to generate closed-loop material movement and to balance industrial development for environmental protection. Hence, integrating indicators for reuse and recycling in SSWM play a critical role in the supply chain. However, the transition process may be insufficient, and the material flow complexities in production and consumption systems need reconceptualization and extensive collaboration among stakeholders (Silva et al., 2017). Due to the exceedingly multilayered nature of material flows in both the supply chain and SWM networks, it is difficult to build a sustainable management system that can tackle any circumstances. While the principal SSWM features treat waste as a resource and strategize for resource supply, pragmatic resource delivery is a requirement to avoid resource inconsistencies within reuse and recycling activities (Patwa et al., 2021). More detail on recyclable resource movements along the supply chain and municipalities is mandatory for a precise analysis of value creation and the economic effects on firms and products (Song et al., 2017; Villalba, 2020). Additionally, future SSWM enhancement should consider the lessons and experiences arising from a variety of industrial cases to avoid reinventing flows and generating best practices, since the international movement toward recyclable resources and materials is increasing.

Corresponding recycling policies could possibly increase the efficacy of pecuniary measures and operating procedures to reduce the municipal waste management burden through restriction on recovery standards, tax strategies, waste charges applied on service users and polluters, thereby benefitting the repossession, reuse and recycling materials trade in secondary markets (Tsai et al., 2021a). However, appropriate execution of these policies remains a challenge (Araya-Córdova et al., 2021; Sukholthaman and Sharp, 2016). The lack of details and clarification of reuse and recycling policy restrictions and the absence of rules and regulations in many developing countries create barriers to developing SSWM. Recycling regulations specifying recycling and waste treatment responsibilities and residential and business payments for recycling and waste disposal are unclear. An adjustment from waste reduction to a sustainable materials policy focused on identifying each specific waste resource is still missing. Therefore, a clear SWM regulatory architecture is needed. Policies to create an ecosystem where firms and cities collaborate as advanced coalitions to encourage SSWM outcomes and sustainable reuse and recycling programs to reinforce waste intervention and environmental standards are needed. Furthermore, regulations on scarce resources and material costs are essential to help firms construct supply chains linked to end-of-life waste materials as returned/recycled inputs to earlier production phases.

Intensive waste management research and development and innovative waste treatment technologies can provide shared models for handling waste facilities and infrastructure including collection instruments, carriages and waste processing methods. The indicator acts as the key to SSWM and is comprised of facilities or services improvement for better waste management quality to meet future sustainability goals. However, negligible technology, missing data, and outdated legal systems exist due to institutional vacuums and misalignment between local and regional governments in many emerging economies (Esmaeilian et al., 2018). Thus, a focus on developing infrastructure, facilities, waste treatment technologies and reliable consistent knowledge and information sources is crucial. For example, continuing investment is needed to support waste reuse and recycling and in the operation and development of SSWM planning and processes. It is recommended that focus be given to nurturing better waste collection and secondary material extraction technologies and to replacing incineration and landfilling. There is also the potential to develop new fuel recovery technologies, such as processing waste into energy, fertilizer or chemicals. It is also suggested that a fiscal valuation be provided for solid waste by incentivizing technologies and strategies that turn waste into other products. However, the core waste treatment technology must synchronize with local architecture, and different methodologies and technologies could initiate unsustainable waste management operations and corrupt sanctions. In developing countries, most of the technologies applied are based on imports with a low level of integration with the local setting, and choosing suitable technologies for each locality poses an imperative duty to promote local environmental security and support socioeconomic progress (Bui et al., 2020a).

6. Conclusion

Many developing and emerging countries have been dealing with the problems of SWM with very restricted means for potentially reusing and recycling materials, substantially downgrading the environment and social health. There is a mass of SSWM literature on how to steer through the challenges and opportunities for both academia and practice. This study aims to propose an integrated model of SSWM and indicate the top important indicators to promote waste reuse and recycling in a developing country. A large SSWM study area, data source diffusion and diverse system restrictions may result in a blur of uncertainty and complexity in the SSWM system and decision-making challenges. Both qualitative and quantitative approaches are incorporated into a hybrid method of content analyses, the FDM, ISM, and FDEMATEL. A systematic data-driven analysis is implemented to deliver state-of-the-art SSWM and assess sustainable solid waste reuse and recycling indicators, thus identifying potential challenges and opportunities for future examination.

The data-driven analysis identified a total of 214 publications from Scopus; 54 keywords were generated, and 19 valid indicators were set into eight levels and grouped into 5 aspects comprising circular resource management, societal requirements, waste features, waste management facilities, and municipal sustainability that are capable of improving SSWM for waste reuse and recycling. The results show that circular resource management, societal requirements, and municipal sustainability are causative aspects. The most prominent indicators are identified as the CE, the informal sector, material flow analysis, policy restrictions, and waste treatment technologies, as these can help to enhance the SSWM system's general performance.

This study enriches the field through both theoretical and practical contributions. An understanding of SSWM knowledge for future work is provided by means of data-driven measurement on an established, valid hierarchical SSWM model, and the causal interrelationships among the attributes are critiqued. The challenges and opportunities for sustainable waste reuse and recycling are highlighted, and the directions for SWM practices in developing countries are established by identifying important indicators as the result of the analytical processes. This study can be considered a site reference for decision makers aiming assimilate sustainable practices; it can help professionals in both academia and practice in all sectors within local, national, and global communities to develop better strategies and visions to intensify SSWM performance through sustainable waste reuse and recycling innovations for forthcoming investigations.

This study has some limitations. It uses the Scopus database, which also includes low-quality sources due to its broad data scope. Using more condensed sources or involving different databases in the measurement process should be considered. The use of expert assessments limits the nature of the hierarchical model, and 30 experts were approached, which may lead to subjective results depending on their experience, knowledge, and acquaintance with the field. Future studies can solve this problem by extending the number of respondents. One country or territory might have its own SSWM features and distinct reuse and recycling characteristics. Future studies can deepen this study within particular countries or regional cases or explore the differences among them to enrich the literature.

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Figure 1. Proposed analysis steps.

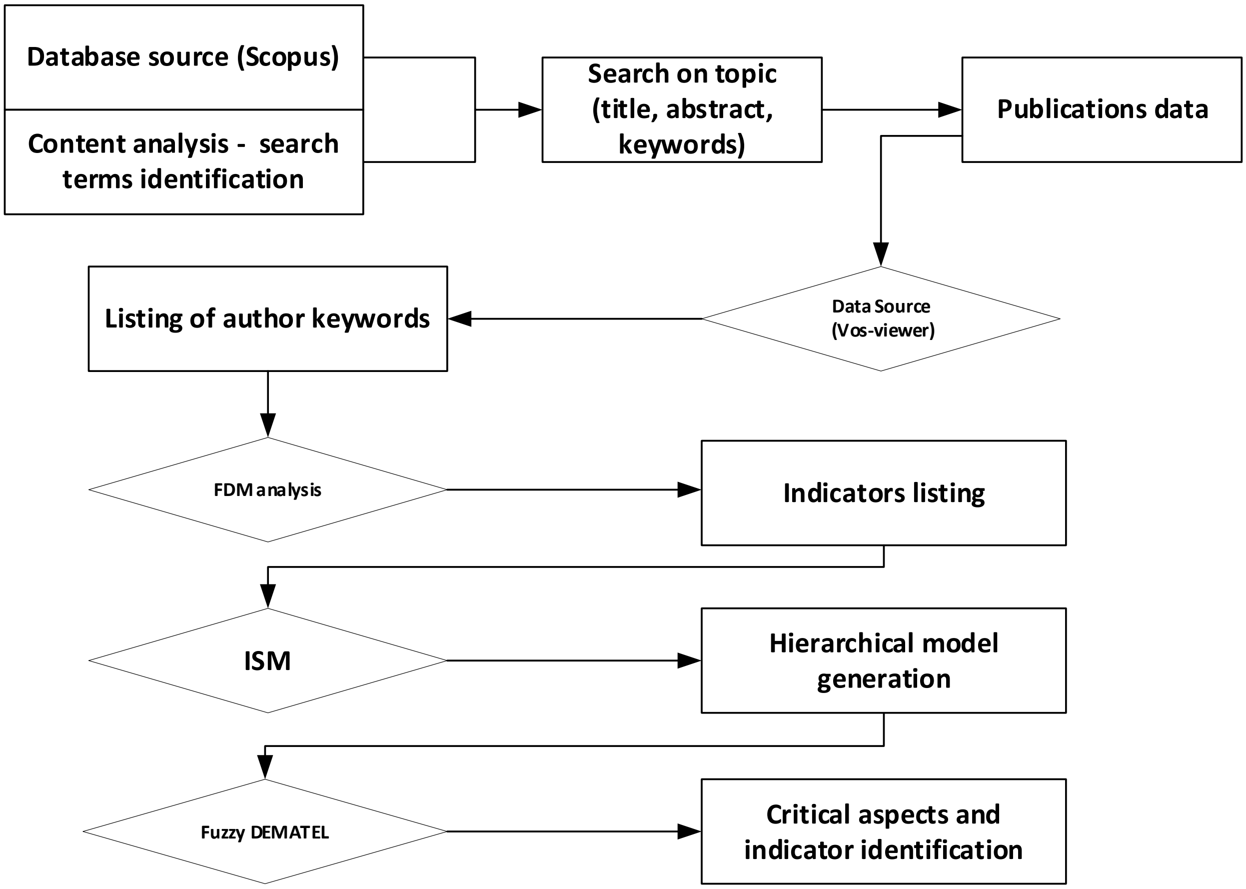

Figure 2. ISM model

Aspect		ISM model			Level
A1	Societal requirement		Community participation (C2)		8
		Informal sector (C6)	Public health (C10)	Public-private partnerships (C11)	7
A2	Circular resource management	Circular economy (C1)	Material flow analysis (C8)	Resource recovery (C12)	6
A3	Municipal sustainability		Political restriction (C9)		5
		Energy demand (C4)	Waste management sustainability (C14)	Sustainable cities (C15)	4
A4	Waste features	E-waste (C3)	Hazardous waste (C5)	Solid waste characteristics (C17)	3
A5	Waste management facility	Technical integration (C7)	Waste treatment technologies (C16)	Waste generation (C19)	2
		Source separation (C13)		Waste collection (C18)	1

Figure 3. Hierarchical model sustainable solid waste reused and recycling in emerging economies

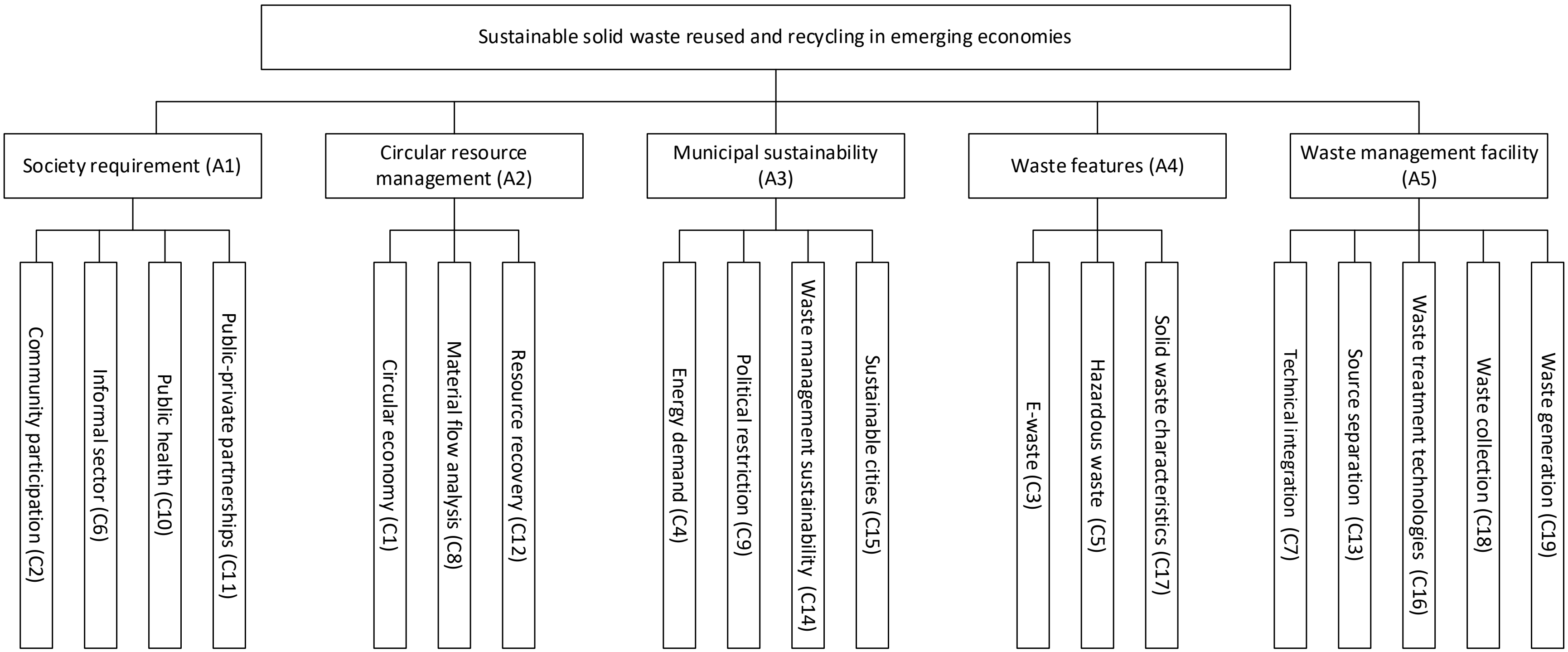

Figure 4. Causal interrelationship among aspects

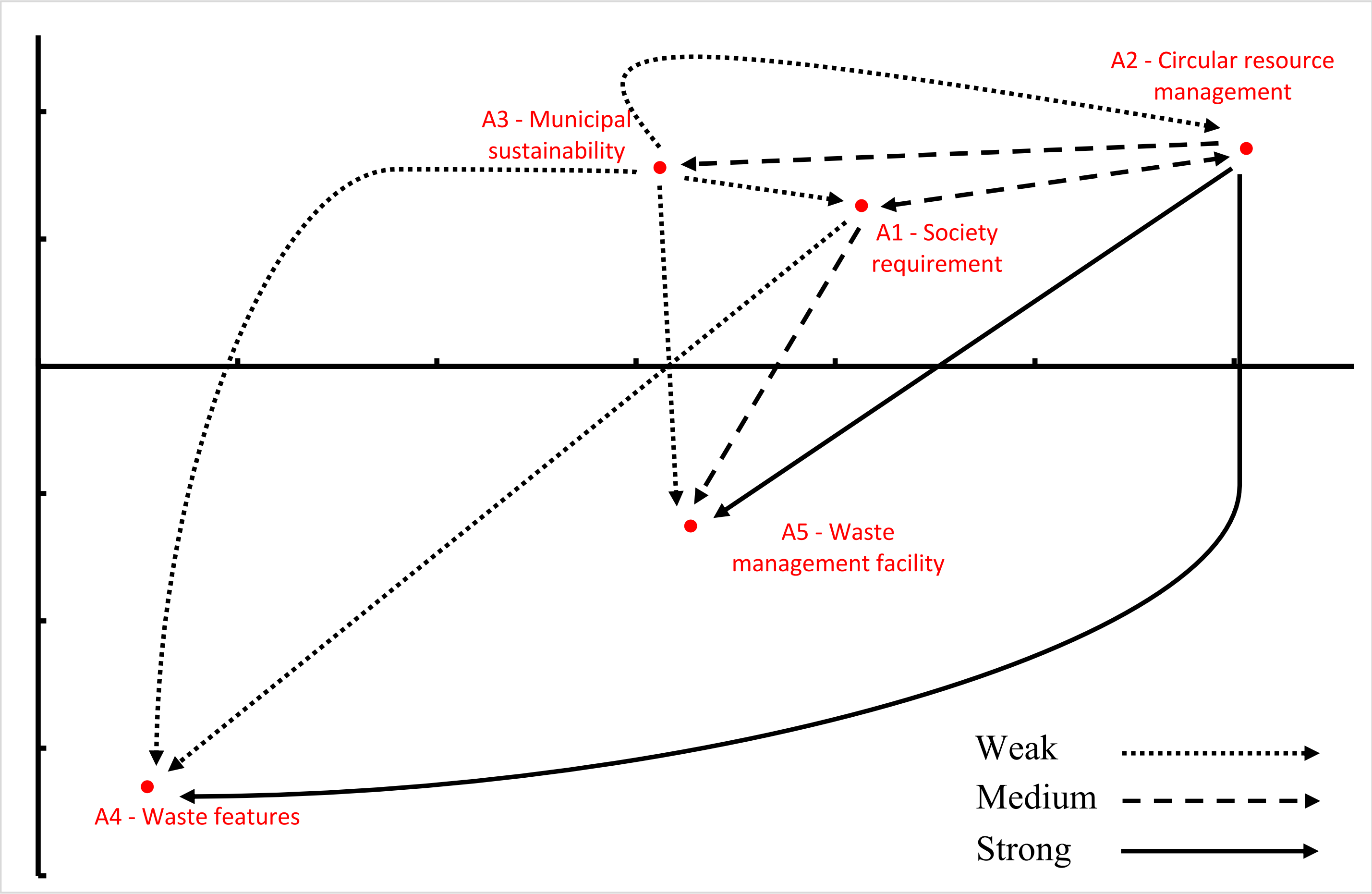

Figure 5. Causal diagram for indicators

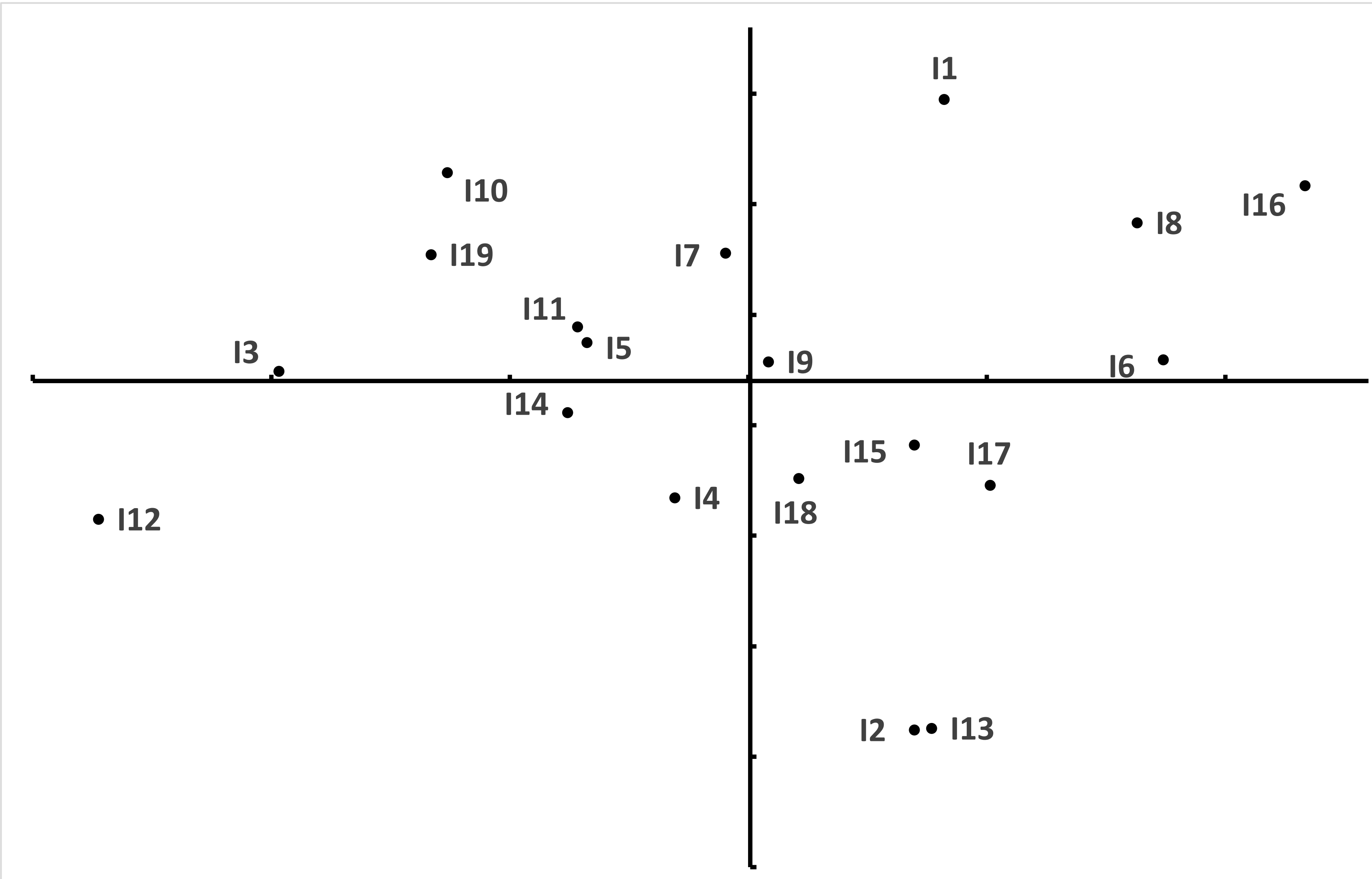

Table 1. FDM linguistic terms' transformation table

Linguistic terms (performance/importance)	Corresponding TFNs
Extreme	(0.75, 1.0, 1.0)
Demonstrated	(0.5, 0.75, 1.0)
Strong	(0.25, 0.5, 0.75)
Moderate	(0, 0.25, 0.5)
Equal	(0, 0, 0.25)

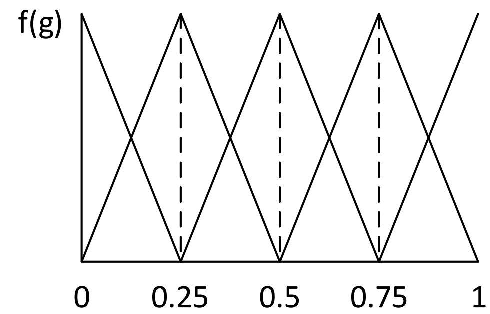

Table 2. Fuzzy DEMATEL linguistic terms' transformation table

Scale	Linguistic variable	Corresponding TFNs
1	No influence	(0.0, 0.1, 0.3)
2	Very low influence	(0.1, 0.3, 0.5)
3	Low influence	(0.3, 0.5, 0.7)
4	High influence	(0.5, 0.7, 0.9)
5	Very high influence	(0.7, 0.9, 1.0)

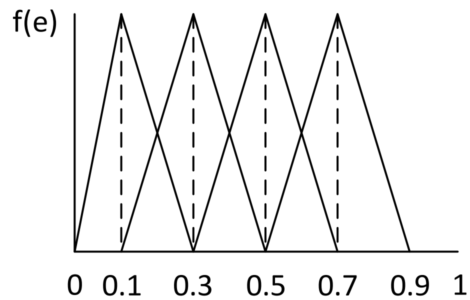

Table 3. Valid indicators from FDM

ID	Indicators
I1	Circular economy
I2	Community participation
I3	E-waste
I4	Energy
I5	Hazardous waste
I6	Informal sector
I7	Integration
I8	Material flow analysis
I9	Policy
I10	Public health
I11	Public-private partnerships
I12	Resource recovery
I13	Source separation
I14	Sustainability
I15	Sustainable cities
I16	Waste treatment technologies
I17	Waste characteristics
I18	Waste collection
I19	Waste generation

Table 4. Contextual relationships matrix of indicator

	I1	I2	I3	I4	I5	I6	I7	I8	I9	I10	I11	I12	I13	I14	I15	I16	I17	I18	I19
I1	V	A	V	A	V	V	O	V	V	V	V	V	V	V	A	A	A	V	-
I2	V	V	V	X	V	V	A	V	A	V	V	V	V	V	V	V	O	-	
I3	X	V	V	V	X	V	A	V	V	V	A	V	A	V	A	V	-		
I4	O	V	O	O	A	X	V	V	O	O	V	O	V	A	V	-			
I5	O	X	A	V	A	V	A	O	O	O	A	O	A	V	-				
I6	V	V	A	O	A	V	A	V	V	V	V	O	A	-					
I7	V	V	V	V	V	A	V	V	V	V	V	V	-						
I8	X	X	A	A	O	X	X	X	A	X	V	-							
I9	X	X	A	A	O	X	A	X	A	X	-								
I10	X	V	A	A	A	X	A	X	A	-									
I11	V	X	A	X	A	V	A	V	-										
I12	V	X	O	O	O	X	O	-											
I13	O	X	O	A	O	V	-												
I14	V	V	A	A	A	-													
I15	V	X	V	A	-														
I16	A	A	A	-															
I17	V	X	-																
I18	A	-																	
I19	-																		

Table 5. Reachability matrix of indicators

	I1	I2	I3	I4	I5	I6	I7	I8	I9	I10	I11	I12	I13	I14	I15	I16	I17	I18	I19
I1	1	0	1	0	1	1	0	1	1	1	1	1	1	1	0	0	1	1	1
I2	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
I3	0	1	1	0	1	0	0	0	0	0	0	0	1	0	0	0	1	1	1
I4	1	1	1	1	0	0	0	0	1	0	0	0	1	0	1	0	1	1	0
I5	0	1	0	1	1	0	0	0	0	0	0	0	1	0	0	0	1	1	1
I6	0	0	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1
I7	0	1	0	1	0	0	1	0	0	0	0	1	1	0	0	1	0	0	0
I8	0	1	1	0	0	1	0	1	1	1	1	1	1	1	0	1	1	1	1
I9	0	1	1	1	1	0	1	0	1	0	0	0	1	1	0	0	1	0	1
I10	1	0	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1	1
I11	1	1	1	1	0	1	1	1	1	1	1	1	1	1	0	1	0	1	1
I12	1	1	1	1	0	1	1	1	1	1	0	1	1	0	0	0	1	1	1
I13	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	1	0	1	1
I14	0	0	1	0	1	0	1	0	0	0	0	0	1	1	1	0	1	1	1
I15	0	1	1	0	1	0	1	0	0	0	1	0	1	0	1	1	0	1	0
I16	0	0	0	0	1	1	0	0	0	0	0	0	0	1	0	1	1	1	0
I17	1	0	0	0	1	0	1	0	0	0	1	0	1	0	1	0	1	0	0
I18	0	0	0	1	0	0	1	0	1	0	0	0	0	0	0	0	0	1	1
I19	0	1	0	1	0	0	0	0	0	0	0	0	0	0	1	1	1	0	1

Table 6. Intersection set of indicators

	I1	I2	I3	I4	I5	I6	I7	I8	I9	I10	I11	I12	I13	I14	I15	I16	I17	I18	I19	**Amount**	**Level**
I1	1	0	1	0	1	1	0	1	1	1	1	1	1	1	0	0	1	1	1	**14**	**6**
I2	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	**17**	**8**
I3	0	1	1	0	1	0	0	0	0	0	0	0	1	0	0	0	1	1	1	**7**	**3**
I4	1	1	1	1	0	0	0	0	1	0	0	0	1	0	1	0	1	1	0	**9**	**4**
I5	0	1	0	1	1	0	0	0	0	0	0	0	1	0	0	0	1	1	1	**7**	**3**
I6	0	0	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	**16**	**7**
I7	0	1	0	1	0	0	1	0	0	0	0	1	1	0	0	1	0	0	0	**6**	**2**
I8	0	1	1	0	0	1	0	1	1	1	1	1	1	1	0	1	1	1	1	**14**	**6**
I9	0	1	1	1	1	0	1	0	1	0	0	0	1	1	0	0	1	0	1	**10**	**5**
I10	1	0	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1	1	**16**	**7**
I11	1	1	1	1	0	1	1	1	1	1	1	1	1	1	0	1	0	1	1	**16**	**7**
I12	1	1	1	1	0	1	1	1	1	1	0	1	1	0	0	0	1	1	1	**14**	**6**
I13	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	1	0	1	1	**5**	**1**
I14	0	0	1	0	1	0	1	0	0	0	0	0	1	1	1	0	1	1	1	**9**	**4**
I15	0	1	1	0	1	0	1	0	0	0	1	0	1	0	1	1	0	1	0	**9**	**4**
I16	0	0	0	0	1	1	0	0	0	0	0	0	0	1	0	1	1	1	0	**6**	**2**
I17	1	0	0	0	1	0	1	0	0	0	1	0	1	0	1	0	1	0	0	**7**	**3**
I18	0	0	0	1	0	0	1	0	1	0	0	0	0	0	0	0	0	1	1	**5**	**1**
I19	0	1	0	1	0	0	0	0	0	0	0	0	0	0	1	1	1	0	1	**6**	**2**

Table 7. SSWM hierarchical framework)

Aspects		Indicators	
A1	Societal involvement	I2	Community participation
		I6	Informal sector
		I10	Public health
		I11	Public-private partnerships
A2	Circular resource management	I1	Circular economy
		I8	Material flow analysis
		I12	Resource recovery
A3	Municipal sustainability	I4	Energy demand
		I14	Waste management sustainability
		I15	Sustainable cities
		I9	Policy restriction
A4	Solid waste features	I3	E-waste
		I5	Hazardous waste
		I17	Waste characteristics
A5	Waste management facility	I7	Technical integration
		I19	Waste generation
		I13	Source separation
		I16	Waste treatment technologies
		I18	Waste collection

Table 8. Initial direction matrix for aspects

	A1	A2	A3	A4	A5
A1	0.693	0.541	0.514	0.501	0.552
A2	0.538	0.684	0.617	0.502	0.508
A3	0.530	0.540	0.716	0.496	0.504
A4	0.495	0.492	0.416	0.729	0.509
A5	0.495	0.524	0.463	0.542	0.712

Table 9. Total interrelationship matrix and cause-and-effect interrelationship among aspects.

	A1	A2	A3	A4	A5	α	β	$(\alpha + \beta)$	$(\alpha - \beta)$
A1	6.572	6.588	6.440	6.547	6.601	32.748	32.116	64.864	0.632
A2	6.629	6.757	6.595	6.663	6.699	33.344	32.485	65.829	0.858
A3	6.477	6.553	6.483	6.511	6.547	32.571	31.788	64.358	0.783
A4	6.104	6.171	6.011	6.239	6.186	30.711	32.361	63.072	(1.649)
A5	6.334	6.417	6.258	6.401	6.496	31.905	32.529	64.435	(0.624)

Table 10. Initial direction matrix for indicators.

	I1	I2	I3	I4	I5	I6	I7	I8	I9	I10	I11	I12	I13	I14	I15	I16	I17	I18	I19
I1	0.771	0.542	0.524	0.507	0.556	0.573	0.495	0.571	0.558	0.557	0.601	0.530	0.554	0.544	0.555	0.496	0.542	0.500	0.513
I2	0.528	0.751	0.517	0.551	0.493	0.526	0.407	0.406	0.520	0.431	0.456	0.512	0.514	0.510	0.519	0.517	0.481	0.530	0.475
I3	0.509	0.509	0.762	0.517	0.492	0.523	0.418	0.443	0.472	0.477	0.494	0.459	0.528	0.516	0.512	0.538	0.528	0.553	0.474
I4	0.548	0.531	0.464	0.775	0.516	0.527	0.522	0.509	0.464	0.456	0.538	0.447	0.502	0.483	0.472	0.479	0.571	0.521	0.469
I5	0.502	0.555	0.475	0.466	0.755	0.540	0.478	0.535	0.474	0.443	0.509	0.525	0.520	0.512	0.530	0.544	0.574	0.538	0.474
I6	0.451	0.571	0.456	0.555	0.545	0.767	0.514	0.468	0.538	0.517	0.558	0.511	0.555	0.578	0.565	0.541	0.542	0.560	0.494
I7	0.494	0.517	0.526	0.481	0.523	0.471	0.759	0.588	0.476	0.473	0.500	0.555	0.525	0.614	0.546	0.490	0.568	0.521	0.531
I8	0.559	0.596	0.519	0.555	0.544	0.550	0.462	0.777	0.538	0.483	0.473	0.497	0.573	0.502	0.568	0.503	0.600	0.604	0.545
I9	0.480	0.557	0.490	0.483	0.492	0.518	0.527	0.506	0.759	0.493	0.469	0.541	0.600	0.546	0.502	0.524	0.538	0.529	0.487
I10	0.464	0.573	0.500	0.504	0.454	0.524	0.529	0.481	0.453	0.764	0.545	0.511	0.607	0.557	0.498	0.520	0.587	0.571	0.453
I11	0.479	0.486	0.516	0.549	0.500	0.527	0.485	0.505	0.503	0.466	0.766	0.476	0.490	0.524	0.515	0.574	0.535	0.545	0.519
I12	0.397	0.529	0.408	0.491	0.502	0.466	0.547	0.512	0.523	0.494	0.397	0.761	0.514	0.453	0.491	0.508	0.484	0.488	0.457
I13	0.420	0.525	0.483	0.481	0.451	0.528	0.505	0.554	0.536	0.516	0.423	0.423	1.000	0.448	0.435	0.515	0.451	0.497	0.462
I14	0.454	0.544	0.480	0.546	0.458	0.488	0.545	0.480	0.507	0.488	0.500	0.475	0.484	0.759	0.546	0.512	0.572	0.477	0.532
I15	0.541	0.570	0.471	0.499	0.481	0.505	0.513	0.519	0.476	0.450	0.493	0.499	0.488	0.450	0.752	0.590	0.586	0.525	0.599
I16	0.543	0.582	0.527	0.613	0.571	0.597	0.558	0.620	0.616	0.585	0.570	0.582	0.573	0.494	0.438	0.766	0.372	0.447	0.541
I17	0.605	0.562	0.556	0.501	0.515	0.533	0.480	0.534	0.571	0.487	0.511	0.523	0.548	0.522	0.556	0.348	0.787	0.500	0.377
I18	0.485	0.528	0.517	0.510	0.516	0.507	0.528	0.496	0.521	0.481	0.527	0.467	0.483	0.450	0.593	0.569	0.472	0.759	0.486
I19	0.511	0.528	0.504	0.519	0.483	0.552	0.545	0.524	0.469	0.480	0.496	0.491	0.501	0.475	0.593	0.548	0.499	0.493	0.754

Table 11. Interrelationship matrix of indicators.

	I1	I2	I3	I4	I5	I6	I7	I8	I9	I10	I11	I12	I13	I14	I15	I16	I17	I18	I19
I1	0.924	0.975	0.896	0.931	0.913	0.948	0.904	0.930	0.925	0.885	0.915	0.904	0.977	0.919	0.943	0.928	0.950	0.935	0.890
I2	0.830	0.919	0.825	0.862	0.835	0.869	0.824	0.841	0.849	0.804	0.830	0.832	0.896	0.844	0.865	0.857	0.870	0.864	0.816
I3	0.836	0.903	0.856	0.866	0.842	0.877	0.832	0.852	0.852	0.815	0.841	0.834	0.906	0.851	0.872	0.866	0.882	0.874	0.823
I4	0.846	0.912	0.834	0.898	0.851	0.884	0.849	0.865	0.857	0.819	0.851	0.839	0.910	0.855	0.875	0.867	0.893	0.877	0.829
I5	0.854	0.928	0.847	0.881	0.887	0.898	0.857	0.881	0.871	0.830	0.861	0.859	0.925	0.870	0.894	0.886	0.906	0.892	0.842
I6	0.876	0.959	0.872	0.918	0.894	0.948	0.888	0.902	0.905	0.864	0.893	0.885	0.958	0.904	0.925	0.914	0.932	0.923	0.871
I7	0.870	0.942	0.869	0.900	0.881	0.909	0.901	0.903	0.889	0.850	0.877	0.879	0.944	0.897	0.913	0.898	0.924	0.908	0.864
I8	0.900	0.976	0.892	0.932	0.908	0.942	0.897	0.946	0.919	0.874	0.899	0.897	0.975	0.911	0.940	0.924	0.952	0.941	0.889
I9	0.858	0.936	0.856	0.890	0.868	0.903	0.869	0.885	0.906	0.842	0.864	0.868	0.941	0.881	0.898	0.891	0.910	0.898	0.850
I10	0.861	0.942	0.861	0.896	0.869	0.908	0.874	0.887	0.881	0.873	0.876	0.869	0.946	0.886	0.902	0.896	0.920	0.907	0.851
I11	0.853	0.922	0.852	0.890	0.863	0.898	0.859	0.879	0.875	0.834	0.887	0.856	0.923	0.873	0.893	0.890	0.904	0.894	0.847
I12	0.799	0.877	0.796	0.837	0.818	0.844	0.820	0.833	0.831	0.792	0.805	0.838	0.877	0.819	0.843	0.837	0.851	0.841	0.796
I13	0.821	0.898	0.823	0.856	0.832	0.871	0.835	0.857	0.852	0.813	0.827	0.824	0.946	0.839	0.858	0.858	0.868	0.862	0.816
I14	0.840	0.917	0.839	0.880	0.849	0.884	0.855	0.866	0.866	0.826	0.851	0.846	0.912	0.885	0.886	0.874	0.897	0.877	0.839
I15	0.863	0.935	0.852	0.890	0.866	0.900	0.866	0.885	0.877	0.836	0.865	0.862	0.928	0.869	0.921	0.896	0.913	0.896	0.859
I16	0.911	0.989	0.905	0.951	0.923	0.960	0.919	0.944	0.940	0.897	0.921	0.918	0.989	0.923	0.940	0.963	0.943	0.939	0.901
I17	0.869	0.934	0.860	0.889	0.868	0.902	0.862	0.885	0.886	0.839	0.866	0.864	0.933	0.876	0.901	0.872	0.932	0.893	0.837
I18	0.848	0.921	0.847	0.881	0.860	0.890	0.858	0.873	0.872	0.830	0.858	0.849	0.917	0.860	0.895	0.885	0.892	0.909	0.839
I19	0.856	0.927	0.852	0.888	0.862	0.901	0.866	0.881	0.872	0.836	0.861	0.858	0.925	0.868	0.902	0.888	0.901	0.889	0.871

Table 12. Cause-and-effect group among indicators.

	α	β	$(\alpha+\beta)$	$(\alpha-\beta)$
I1	17.593	16.317	33.910	1.277
I2	16.135	17.712	33.847	(1.578)
I3	16.281	16.235	32.516	0.046
I4	16.410	16.936	33.345	(0.526)
I5	16.669	16.492	33.161	0.176
I6	17.233	17.136	34.369	0.098
I7	17.017	16.435	33.452	0.581
I8	17.516	16.799	34.315	0.717
I9	16.815	16.727	33.541	0.088
I10	16.907	15.962	32.868	0.945
I11	16.694	16.447	33.141	0.247
I12	15.757	16.381	32.137	(0.624)
I13	16.157	17.727	33.884	(1.570)
I14	16.490	16.630	33.120	(0.140)
I15	16.780	17.067	33.847	(0.287)
I16	17.775	16.890	34.666	0.885
I17	16.769	17.238	34.007	(0.469)
I18	16.583	17.022	33.605	(0.438)
I19	16.704	16.130	32.834	0.573
Average			33.504	0.000

Appendix A. Expert's demography

Expert	Position	Education levels	Years of experience	Organization type (academia/practice)	Nationality
1	Professor	Ph.D.	12	Academia	Taiwan
2	Professor	Ph.D.	11	Academia	Taiwan
3	Professor	Ph.D.	8	Academia	China
4	Professor	Ph. D	15	Academia	Chile
5	Professor	Ph.D.	9	Academia	Hongkong
6	Professor	Ph.D.	16	Academia	Korea
7	Associate Professor	Ph.D.	10	Academia	Vietnam
8	Associate Professor	Ph.D.	14	Academia	Vietnam
9	Distinguished Professor	Ph.D.	15	Academia	Malaysia
10	Distinguished Professor	Ph.D.	13	Academia	Indonesia
11	Distinguished Professor	Ph.D.	8	Academia	Indonesia
12	Distinguished Professor	Ph.D.	10	Academia	Brazil
13	Assistant Professor	Ph.D.	9	Academia	Afghanization
14	Assistant Professor	Ph.D.	6	Academia	Bangladesh
15	Researcher & Section Chief (Professor)	Ph.D.	9	NGOs (Research center)	Iran
16	Researcher	Ph.D.	14	Government (Research center)	Indonesia
17	Researcher	Master	7	NGOs (Research center)	Brazil
18	Deputy Director of Institute	Master	8	Government (Research center)	North America
19	Vice Deputy Director of Institute	Master	5	Government office	Cameroon
20	Vice Deputy Director of Institute	Ph.D.	9	Government office	Vietnam
21	Production Executive	Ph.D.	14	Practices	Brazil
22	Operation Manager	Master	7	Practices	Chile
23	Operation Manager	Ph.D.	9	Practices	Vietnam
24	Executive manager	Master	11	Practices	Taiwan
25	Recycling Project manager	Master	10	Practices	Bangladesh
26	Recycling Project manager	Master	12	Practices	Indonesia
27	Recycling Project manager	Master	6	Practices	Indonesia
28	Production Executive	Ph.D.	8	Practices	Vietnam
29	Business Executive	Master	9	Practices	Taiwan
30	Business Executive	Master	6	Practices	Malaysia

The expert committee was approach thanks to the connections of Institute of Innovation and Circular Economy, Asia University, Taiwan.

Appendix B. Refine author keywords listing

Anaerobic digestion
Biogas
Biomass
Carbon footprint
Circular economy
Community participation
Composting
Construction and demolition waste
Cost recovery
E-waste
Energy
Energy recovery
Environment
Governance
Hazardous waste
Household solid waste
Indiscriminate dumping
Informal recycling
Informal sector
Integration
Landfill
Legislation
Material flow analysis
Material recovery
Municipality
Organic waste
Policy
Poverty alleviation
Privatization
Public health
Public participation
Public policies
Public-private partnerships
Recycling
Reduce
Resource recovery
Reuse
Sanitary landfill
Scavenging

Selective collection
Source separation
Sustainability
Sustainable cities
Technologies
Urbanization
Vermicomposting
Waste characteristics
Waste collection
Waste composition
Waste disposal
Waste generation
Waste minimization
Waste pickers
Waste-to-energy

Appendix C. FDM Result

Keywords	l_e	u_e	S_e	Decision
Anaerobic digestion	0.000	0.500	0.250	Unaccepted
Biogas	0.000	0.500	0.250	Unaccepted
Biomass	0.000	0.500	0.250	Unaccepted
Carbon footprint	0.000	0.500	0.250	Unaccepted
Circular economy	(0.378)	0.878	0.345	Accepted
Community participation	(0.332)	0.832	0.333	Accepted
Composting	0.000	0.500	0.250	Unaccepted
Construction and demolition waste	0.000	0.500	0.250	Unaccepted
Cost recovery	0.000	0.500	0.250	Unaccepted
E-waste	(0.058)	0.933	0.452	Accepted
Energy	(0.017)	0.892	0.442	Accepted
Energy recovery	0.000	0.500	0.250	Unaccepted
Environment	0.000	0.500	0.250	Unaccepted
Governance	0.000	0.500	0.250	Unaccepted
Hazardous waste	(0.390)	0.890	0.348	Accepted
Household solid waste	0.000	0.500	0.250	Unaccepted
Indiscriminate dumping	0.000	0.500	0.250	Unaccepted
Informal recycling	0.000	0.500	0.250	Unaccepted
Informal sector	(0.014)	0.889	0.441	Accepted
Integration	(0.291)	0.791	0.323	Accepted
Landfill	0.000	0.500	0.250	Unaccepted

Legislation	0.000	0.500	0.250	Unaccepted
Material flow analysis	(0.353)	0.853	0.338	Accepted
Material recovery	0.000	0.500	0.250	Unaccepted
Municipality	0.000	0.500	0.250	Unaccepted
Organic waste	0.000	0.500	0.250	Unaccepted
Policy	(0.380)	0.880	0.345	Accepted
Poverty alleviation	0.000	0.500	0.250	Unaccepted
Privatization	0.000	0.500	0.250	Unaccepted
Public health	(0.317)	0.817	0.329	Accepted
Public participation	0.000	0.500	0.250	Unaccepted
Public policies	0.000	0.500	0.250	Unaccepted
Public-private partnerships	(0.389)	0.889	0.347	Accepted
Recycling	0.000	0.500	0.250	Unaccepted
Reduce	0.000	0.500	0.250	Unaccepted
Resource recovery	(0.312)	0.812	0.328	Accepted
Reuse	0.000	0.500	0.250	Unaccepted
Sanitary landfill	0.000	0.500	0.250	Unaccepted
Scavenging	0.000	0.500	0.250	Unaccepted
Selective collection	0.000	0.500	0.250	Unaccepted
Source separation	(0.297)	0.797	0.324	Accepted
Sustainability	(0.405)	0.905	0.351	Accepted
Sustainable cities	(0.038)	0.913	0.447	Accepted
Technologies	(0.421)	0.921	0.355	Accepted
Urbanization	0.000	0.500	0.250	Unaccepted
Vermicomposting	0.000	0.500	0.250	Unaccepted
Waste characteristics	(0.383)	0.883	0.346	Accepted
Waste collection	(0.027)	0.902	0.444	Accepted
Waste composition	0.000	0.500	0.250	Unaccepted
Waste disposal	0.000	0.500	0.250	Unaccepted
Waste generation	(0.413)	0.913	0.353	Accepted
Waste minimization	0.000	0.500	0.250	Unaccepted
Waste pickers	0.000	0.500	0.250	Unaccepted
Waste-to-energy	0.000	0.500	0.250	Unaccepted
Threshold μ			0.292	

Appendix D. The fuzzy direct relation matrix and the defuzzification for aspects sample (Respondent 1)

		A1				A2				A3				A4				A5		
A1		[1.000	1.000	1.000]		[0.500	0.700	0.900]		[0.700	0.900	1.000]		[0.500	0.700	0.900]		[0.700	0.900	1.000]
A2		[0.500	0.700	0.900]		[1.000	1.000	1.000]		[0.700	0.900	1.000]		[0.100	0.300	0.500]		[0.100	0.300	0.500]
A3		[0.500	0.700	0.900]		[0.500	0.700	0.900]		[1.000	1.000	1.000]		[0.500	0.700	0.900]		[0.500	0.700	0.900]
A4		[0.500	0.700	0.900]		[0.500	0.700	0.900]		[0.700	0.900	1.000]		[1.000	1.000	1.000]		[0.700	0.900	1.000]
A5		[0.500	0.700	0.900]		[0.700	0.900	1.000]		[0.500	0.700	0.900]		[0.700	0.900	1.000]		[1.000	1.000	1.000]
		$\bar{e}_{\ell bc}^{a}$	$\bar{e}_{m bc}^{a}$	$\bar{e}_{r bc}^{a}$		$\bar{e}_{\ell bc}^{a}$	$\bar{e}_{m bc}^{a}$	$\bar{e}_{r bc}^{a}$		$\bar{e}_{\ell bc}^{a}$	$\bar{e}_{m bc}^{a}$	$\bar{e}_{r bc}^{a}$		$\bar{e}_{\ell bc}^{a}$	$\bar{e}_{m bc}^{a}$	$\bar{e}_{r bc}^{a}$		$\bar{e}_{\ell bc}^{a}$	$\bar{e}_{m bc}^{a}$	$\bar{e}_{r bc}^{a}$
A1	**0.500**	[1.000	0.600	0.200]	**0.500**	[0.000	0.000	0.000]	**0.500**	[0.400	0.400	0.200]	**0.900**	[0.444	0.444	0.444]	**0.900**	[0.667	0.667	0.556]
A2		[0.000	0.000	0.000]		[1.000	0.600	0.200]		[0.400	0.400	0.200]		[0.000	0.000	0.000]		[0.000	0.000	0.000]
A3		[0.000	0.000	0.000]		[0.000	0.000	0.000]		[1.000	0.600	0.200]		[0.444	0.444	0.444]		[0.444	0.444	0.444]
A4		[0.000	0.000	0.000]		[0.000	0.000	0.000]		[0.400	0.400	0.200]		[1.000	0.778	0.556]		[0.667	0.667	0.556]
A5		[0.000	0.000	0.000]		[0.400	0.400	0.200]		[0.000	0.000	0.000]		[0.667	0.667	0.556]		[1.000	0.778	0.556]
		L_{bc}^{a}	R_{bc}^{a}			L_{bc}^{a}	R_{bc}^{a}			L_{bc}^{a}	R_{bc}^{a}			L_{bc}^{a}	R_{bc}^{a}			L_{bc}^{a}	R_{bc}^{a}	
A1		1.000	0.333			0.000	0.000			0.400	0.250			0.444	0.444			0.667	0.625	
A2		0.000	0.000			1.000	0.333			0.400	0.250			0.000	0.000			0.000	0.000	
A3		0.000	0.000			0.000	0.000			1.000	0.333			0.444	0.444			0.444	0.444	
A4		0.000	0.000			0.000	0.000			0.400	0.250			1.000	0.714			0.667	0.625	
A5		0.000	0.000			0.400	0.250			0.000	0.000			0.667	0.625			1.000	0.714	
		CP_{bc}^{a}				CP_{bc}^{a}				CP_{bc}^{a}				CP_{bc}^{a}				CP_{bc}^{a}		
A1		0.333				0.000				0.356				0.444				0.639		
A2		0.000				0.333				0.356				0.000				0.000		
A3		0.000				0.000				0.333				0.444				0.444		
A4		0.000				0.000				0.356				0.714				0.639		
A5		0.000				0.356				0.000				0.639				0.714		
		dr_{bc}				dr_{bc}				dr_{bc}				dr_{bc}				dr_{bc}		
A1		0.667				0.500				0.678				0.500				0.676		
A2		0.500				0.667				0.678				0.100				0.100		
A3		0.500				0.500				0.667				0.500				0.500		
A4		0.500				0.500				0.678				0.743				0.676		
A5		0.500				0.678				0.500				0.676				0.743		