Investigating Circular Economy Barriers for Construction and Demolition Waste in the Construction Industry: A Delphi and Interpretive Structural Modelling Approach

Ajisomo, T, Saka, A.B., Dauda, J.A and Osuolale, M

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Abstract

Purpose: This study examines the barriers to circular economy (CE) implementation for construction and demolition (C&D) waste management. The study aims to enhance the understanding of CE barriers and their interrelationships, facilitating targeted, context-specific interventions for sustainable waste management in developing economies.

Design/methodology/approach: A pluralistic method was adopted, including a critical review of literature, a two-round Delphi survey utilising 22 and 17 experts, and interpretive structural modelling (ISM) with nine (9) experts in the Nigerian setting. Expert consensus on key barriers was established in the Delphi second round. Mean score ranking and inter-rater analysis were used to analyse Delphi responses, while ISM-based analysis and Matrice d'Impacts croises-multipication applique a classement analysis (MICMAC) were used to explore contextual relationships between the barriers.

Findings: The analysis revealed the significance of all examined barriers. The most crucial barriers include the pursuit of short-term profitability, insufficient construction waste data, lack of understanding, and scarce funding. Equally, regulatory and supply chain followed by economic barriers, emerged as the most significant categories. ISM introduced a hierarchical model for the barriers, further classifying them into dependent, linkage, and independent categories. Understanding these interactions provides a basis for prioritising interventions.

Originality/value: This research presents a novel, structured analysis of the complex barriers to CE implementation in C&D waste management within the construction industry, particularly in developing economies. The findings offer practical insights for policymakers and industry stakeholders to address these barriers in order of influence and criticality, thereby advancing sustainability and circularity in the construction sector.

Keywords: Circular Economy, Construction and Demolition Waste, Delphi, Interpretive Structural Modelling, Construction Industry, Waste Management

Paper type: Research paper

1. Introduction

The construction industry accounts for 6.2% of the global GDP, per Eurostat (2023). The sector, globally, however, consumes about 30% of raw materials, produces over 33% of CO_2 emissions and contributes up to 35% of landfill waste (Huang et al., 2018a; Solís-Guzmán et al., 2009). These issues are further escalated by the increase in world population, from the current 7.7 billion to 9.8 billion by 2050 (United Nations, 2019), leading to a rise in construction activities due to rapid urbanisation (Addai et al., 2022). A shift to a circular economy (CE) emphasises resource efficiency and waste reduction and is therefore regarded as a practical solution to the status quo (Ellen MacArthur Foundation [EMF], 2021; Linder & Williander, 2017). CE involves reusing, recycling, and repairing materials to elongate their lifecycle and minimise waste (Bocken & Short, 2020; Díaz-López et al., 2021) while sustaining the economy, yielding significant economic benefits, and potentially saving over $100 billion annually (Guerra et al., 2021). However, despite the clear benefits, its adoption in the construction sector of developing nations remains limited (Bassi & Dias, 2019; Korhonen et al., 2018; Zuofa et al., 2023).

In the last decade, within the Nigerian Construction Industry (NCI), empirical investigations (Aboginije et al., 2021; Ajayi et al., 2016; Ogunmakinde et al., 2024) have expounded on the state of the art regarding C&D waste management, suggesting that the sector is characterised by practices that often generate waste throughout the construction value chain. Ajayi et al. (2016) assert that waste generation in all phases of construction is caused by bulk procurement and unutilised materials, further compounded by the unpredictable, complex nature of construction projects and the extreme scheduling and financial constraints that hinder proper waste monitoring (Kareem et al., 2015). Thus, a significant amount of construction waste ends up in unauthorised landfills as a result of ineffective disposal techniques. Inadequacies in design (Aboginije et al., 2021) and lack of waste valuation (Adewuyi et al., 2014; Ogunmakinde et al., 2019) are major influencing factors, resulting from poor regulations and inadequate execution of a sustainable procurement process. While recycling of certain C&D waste, especially steel, is a common practice in Nigeria (Aboginije et al., 2021), inadequacy in regulation enforcement leads to a lackadaisical attitude in NCI as waste management procedures prioritise convenience, jeopardising environmental responsibility (Ajayi et al., 2015). Popoola et al. (2018) argued for the contribution of the informal private sector to waste disposal and ecological protection, highlighting the importance of comprehensive surveys in obtaining reliable statistics on waste generation. Furthermore, the composition nature of construction waste (e.g., concrete, plastics, steel, plywood, etc.) challenges the sorting process for recycling (Akinade et al., 2017).

Moreover, lack of understanding among the industry stakeholders poses yet another crucial challenge to sustainable waste management in the Nigerian construction industry. As highlighted by Aboginije et al. (2021), significant knowledge gaps on proper handling and disposal of construction waste persist, preventing sufficient segregation at the source and, as a result, impeding successful recycling initiatives. It is, therefore, crucial to initiate a paradigm shift toward sustainable waste management to bridge this gap. In light of this, Ajayi et al. (2008) recommend on-site assessment, identification of waste streams, waste segregation, identification of final destination, and examination of on-site protocols as vital steps in waste handling. These processes can be optimised with the help of digital tools such as Building Information Modelling (BIM) (Eze et al., 2022). However, for effective implementation, it is necessary to establish laws and a regulatory system for sustainable waste management (Akujieze & Idehai, 2014).

As the NCI continues to follow a linear model of production and resource utilisation, it is imperative to explore the challenges contributing to low application of CE practices for minimising and managing C&D waste among the stakeholders in a developing economy context. Hence, the urgent need to investigate this issue in a bid to understand the underlying barriers to CE implementation and develop strategies to curb them. Furthermore, existing accounts fail to explore the dynamic relationships between these barriers. Therefore, this study aims to bridge this gap by investigating the barriers to the implementation of CE strategies for C&D waste within the developing economy context of the NCI and establishing the contextual relationships between them. This study, therefore, presents three objectives: To (1) identify the barriers to CE implementation for C&D waste management in the construction sector of developing economies, (2) assess the importance level of the barriers, and (3) examine the dynamic relationships that exists between these barriers. Understanding the barriers and how they interact with one another is crucial for developing sustainable strategies to enhance C&D waste management by the concerned stakeholders. This research will contribute significantly to the body of knowledge on CE in the NCI and construction sectors of other infant economies, offering opportunities for policy and practice improvement.

The rest of the paper is structured as follows: Section 2 reviews related literature on barriers to CE implementation for C&D waste management in the construction industry; section 3 focuses on the research methodology; sections 4 and 5 present the data analysis and findings, respectively; and lastly, the key findings, limitations and implications of the study are presented in the conclusion part (section 6).

2. Literature review

2.1 Barriers to circular C&D waste management in emerging economies

Given the continued significant consumption of resources and ensuing environmental impact of waste generation in construction processes, it is particularly significant to incorporate CE principles in C&D waste management to foster sustainable development (Bhavsar et al., 2023; Ding et al., 2023). However, within the construction domain of developing economies, various barriers impede the uptake and application of CE principles in the management of C&D waste, restricting acceptance of circular practices towards a more resource-efficient and sustainable model (Bello et al., 2024). This, for instance, includes weak regulation as a result of fragmented governance and skills gaps, which largely contrasts the reality in more advanced economies (Hammadhu & Anjali, 2024; Lu et al., 2023). Literature consistently highlights that these barriers are not isolated but form a complex, interconnected system (Ding et al., 2023; Véliz et al., 2023). These challenges extend beyond technical limitations to encompass organisational dynamics and the broader environmental context, with competing stakeholder priorities and conflicting policies frequently stalling progress toward sustainable resource consumption and waste management (Mahpour, 2018). Without an evidence-based appreciation of these contextual barriers, CE strategies risk being poorly adopted and ineffectively implemented, contributing to misalignment with the socio-economic realities. Therefore, relevant studies addressing CE implementation challenges specifically for C&D waste are assiduously retrieved from SCOPUS and Google Scholar databases for assessment. Consequently, the United Nation's World Economic Situation and Prospects' country classification (United Nations, 2023) was adopted as a basis to identify emerging economies and map pertinent studies.

Recognising the complexity of CE barriers within construction, this study draws from the theoretical lenses of the technology, organisation and environment (TOE) framework (Tornatzky et al., 1990), offering multi-dimensional perspectives to CE challenges for C&D waste management. The TOE framework encases the fundamental dimensions and interplay of technology, organisation, and environment, providing a comprehensive theoretical foundation (Baker, 2012), and it has gained traction for its holistic approach in analysing innovation adoption within diverse CE contexts (e.g., Natrajan et al., 2024; Oluleye et al., 2024). The framework is particularly relevant to construction, where successful deployment of innovative and CE practices relies on synergistic advancements in technology adoption, organisational readiness, and enabling policy environments (Oluleye et al., 2024; Shukla & Shankar, 2022). Thus, adopting the TOE framework enables the study to benefit from the understanding of the internal (i.e., technology and organisation contexts) and the external (i.e., environmental context) factors affecting CE implementation. Table 1, in addition to mapping the 20 CE barriers for C&D waste management across TOE dimensions, presents a consolidated thematic classification of the barriers into four distinct clusters: knowledge and

awareness, economic, regulatory and supply chain, and technical and resource barriers, addressing the first research objective. Each thematic grouping of the barriers is discussed subsequently.

Insert Table 1

2.1.1 Knowledge and awareness barriers

The related barriers describe the significant lack of understanding of CE principles for handling C&D waste and their resulting benefits among construction stakeholders. It equally reflects the behavioural attitude of the public towards accepting CE. A primary barrier in CE literature in emerging economies is the prevalent lack of awareness and knowledge regarding CE. For instance, Wijewansha et al. (2021) argued that lack of understanding of the CE concept is a major hindrance to CE adoption in Sri Lanka. While this finding highlights the practice of the early construction phase stakeholders, it reflects the reality of actors across the construction value chain. Likewise, the submissions of AlJaber et al. (2024) and Bhavsar et al. (2023) in Saudi Arabia and India, respectively, further reinforce that the knowledge gaps contribute to inefficient circular waste handling and management practices in emerging economies.

The knowledge inadequacy outspreads to the conservative nature of the construction sector, restraining the opportunities and benefits CE practices offer for C&D waste management (Oluleye et al., 2022). For example, the fixed mental models of the construction sector on traditional approaches to C&D waste influence cultural resistance to innovative concepts like the CE, as stakeholders are unfamiliar with CE benefits and feasibility (Papamichael et al., 2023), while continue reliance on traditional linear economy practices contribute to the reluctance towards the uptake of CE practices (Karaca & Tleuken, 2024). This necessitate improved education through operational training and awareness campaigns to empower stakeholders to make informed decisions and develop the competencies required to implement CE strategies effectively (Silva et al., 2024; Zuofa et al., 2023). However, contention regarding CE awareness level in emerging economies exists in literature. For instance, Zuofa et al. (2023) argued that construction stakeholders in Sub-Saharan Africa, including the small and medium enterprises (SMEs), surprisingly, possess a reasonable level of CE awareness, further suggesting that the degree of awareness may be impacted by different factors, including the sector and business settings, rather than just location. This, therefore, indicate that while knowledge gaps are prevalent, the extent and impact may vary across regions and contexts.

2.1.2 Economic barriers

Economic barriers are widely cited in literature, and they refer to limitations related to funding, financial support, and economic viability of CE investments. Cost, as one of the key determinants of project success, influences the decisions of construction stakeholders, who often prioritise short-term profitability of the conventional practices due to budget constraints as against long-term sustainability benefits of adopting CE in managing waste in construction projects and at its end-of-life (AlJaber et al., 2023; Rahigude et al., 2022). Ding et al. (2023) argued the cost-intensiveness of circular practices for managing buildings and C&D waste, such as deconstruction and recycling, compared to traditional demolition due to higher labour and time requirements. Similarly, Bao et al. (2020) highlighted that implementing on-site recycling is relatively costly, contributing to the vulnerable business case of the CE. These economic challenges are often compounded by an unclear financial case for the long-term benefits of CE, complicating the justification for initial investment (AlJaber et al., 2024; Suleman et al., 2023). Hence, driving clients and construction firms to opt for the conventional practice with immediate profit (Véliz et al., 2023).

The low price of virgin materials coupled with the lack of financial incentive to reuse and incorporate C&D waste in new construction projects undermines the market for secondary materials (Karaca & Tleuken, 2024; Suleman et al., 2023) and diminishes the economical attractiveness of recycled alternatives (Bhavsar et al., 2023; Hentges et al., 2022). Consequently, recycled C&D waste materials are generally not competitively priced (Ding et al., 2023), while the perceived benefits of recycling and reuse are usually outweighed by the costs (Bhavsar et al., 2023; Véliz et al., 2023). Moreover, the market for circular buildings that incorporate C&D waste is often insufficient (AlJaber et al., 2024; Mahpour, 2018). Therefore, budget consideration for circular waste management coupled with the provision of fiscal incentives influences the economic viability of CE and motivates its implementation for C&D waste (Liu et al., 2021; Zuofa et al., 2023). Hence, there exist disparity and insufficiency of economic models and incentives needed to support the implementation of CE in construction to sustainably manage its waste (Liu et al., 2021).

2.1.3 Regulatory and supply chain barriers

This set of barriers combines government and institutional challenges, and it describes the deficiencies in policies, standards, and coordination within the construction value chain in driving sustainable C&D waste management. From C&D waste management practice, policies and regulations present a significant challenge to CE implementation, including weak policies and inconsistent regulatory frameworks across different regions, as supported by Mahpour (2018), noting conflicting interests and varying priorities in policy development. Likewise, Oluleye et al. (2023) concurred with Costa et al. (2022), emphasising that a

non-cohesive regulatory framework could lead to biased data and uneven CE implementation. While policies and regulatory frameworks guiding C&D waste management exist in some regions, challenges regarding enforcement persist (Alite et al., 2023; Hentges et al., 2022). Additionally, the construction industry is characterised by a complex supply chain and siloed working practices, which exacerbates the regulatory challenges (Alite et al., 2023), as evident in the lack of collaboration among the key stakeholders in fostering CE uptake (Lu et al., 2023). Thus, a lack of a holistic regulatory approach limits the transition to a CE in the construction industry, especially for minimising C&D waste.

2.1.4 Technical and resource barriers

Several technical and resource-related barriers describing the practical and material constraints that hinder CE adoption for C&D waste impede CE implementation in the construction industry were identified. It includes issues arising from building design through the end-of-life phase and consideration for adequate waste management, which promotes circularity. As noted by AlJaber et al. (2024), the intricacy of building materials and structures and the design challenges associated with product recovery and reuse, make circular design challenging. This is further emphasised by Aboginije et al. (2023), who agreed with Véliz et al. (2023) that this complexity points to the lack of effective storage for end-of-life assets and the poor tracking of material flow in a standardised material bank and thus, impedes the implementation of CE within the construction supply chain. Additionally, low material quality and reliability of retrieved material properties hinder reuse and recycling of C&D waste (Alite et al., 2023; Bao et al., 2020). Moreover, the quality challenge is complicated by the poor choice of design and construction practices that prevent material saving, which prevents easy sorting and recovery (Torgautov et al., 2021). Hence, overcoming these barriers requires the development of robust frameworks for material tracking and quality assurance to ensure efficient waste recovery for recycling and diversion from landfills.

3. Methodology

The study employed a quantitative research method via the Delphi and Interpretive Structural Modelling (ISM) survey to collect data on barriers to CE implementation for C&D waste in the developing economy context of Nigeria. A positivist approach grounded in objective epistemology was adopted by the study, aligning with quantitative research (Saunders et al., 2019). The study was conducted in sequential steps as shown in Figure 1. Data was collected through two Delphi survey rounds from Nigerian construction industry professionals to examine the barriers identified in the literature. This method is appropriate for attaining consensus among experts on multidisciplinary issues like CE and C&D waste management, a relatively new field of study in developing nations (Campbell-Johnston et al., 2021; Esa et al., 2017). As such, purposive sample strategy, a non-probabilistic sampling was adopted based on certain

predetermined criteria due to the limited experts in CE and sustainable C&D waste management within the NCI (Okoh et al., 2024). Therefore, the process includes careful selection of experts who are rich in knowledge, available and committed to participating in multiple Delphi rounds. Hence, construction practitioners who have demonstrated expertise in sustainable construction, C&D waste management, or circular construction practices within the NCI were targeted. This resulted in the participation of experts with substantial knowledge of the phenomenon under study (CE and C&D waste) in the Delphi survey as evidenced experts' qualifications and experience in a later section (4.1), thus ensuring accuracy and reliability in the information retrieved from the experts.

Out of the 35 experts targeted for the survey, only 17 experts completed both Delphi rounds, a decrease of 5 experts as compared to the response in the first round (22). Since a minimum of seven (7) panellists is deemed sufficient, this is acceptable (Hon et al., 2011). Saka et al. (2020) and Olawumi & Chan (2019) used 17 and 14 respondents, respectively. As in related investigations (Campbell-Johnston et al., 2021; Saka & Chan, 2020a), e-Delphi was communicated via email to the recruited experts, and the survey spanned over a period of four months. The survey was discontinued after two rounds, after stability of responses. Literature reveals disagreement on the consensus definition; thus, the researcher must define consensus to interpret results (Diamond et al., 2014), which is the stability in the mean of subsequent rounds (Saka et al., 2022).

The Delphi questionnaire was structured into two parts. The first part requests expert demographics to determine their degree of competence in CE and C&D waste management (Hamma-adama et al., 2018). The second section requests information on implementation barriers to CE, adopting a 5-point Likert scale spanning from strongly disagree (1) to strongly agree (5). This measurement scale was chosen because it has a lower margin of error, provides options without overwhelming respondents, and can effectively assess expert opinions (Liu et al., 2021; Oluleye et al., 2023; Saka et al., 2022). A pilot study with four participants was conducted to assess the validity of the Delphi questionnaire. The data was evaluated, and findings were used to make necessary adjustments.

Insert Figure 1

ISM was first presented by Warfield in 1974. It uses expert knowledge to disintegrate complicated systems into smaller subsystems and then develops a multi-level structural model to comprehend their complex relationships, making it suitable for investigating CE implementation barriers and underlying relationships

between them. As a result of prioritising response quality over quantity, fewer respondents are usually recruited for ISM (Shen et al., 2016). This approach, due to its high efficiency, has been widely used in construction management studies (Ahuja et al., 2017; Chaple et al., 2018; Saka et al., 2020; Saka & Chan, 2020b; Shen et al., 2016) for analysing and examining variables in intricate systems. However, there is disagreement in the literature regarding the minimum number of participants. Mitra Debnath & Shankar (2012) used two experts, Shen et al. (2016) and Gift et al. (2023) used five experts, while Ahuja et al. (2017) consulted seven experts. Hence, nine (9) responses were gotten from the 15 experts who were invited from the Delphi pool, which is deemed sufficient based on procedure in similar studies. The ISM questionnaire was pilot tested with two experts to test its reliability. This project received ethical clearance in line with the Research Policy and Procedures of Leeds Beckett University, UK with application reference number 117596.

3.1 Data analysis techniques

Descriptive and inferential statistical methods were used to assess the responses of the NCI stakeholders. To check for normality and reliability of the data collection instrument, Shapiro-Wilk test (Ghasemi & Zahediasl, 2012) and Cronbach alpha reliability test (Sürücü & Maslakçi, 2020) were conducted, respectively. Mean score was computed for ranking CE implementation barriers, while Kendall concordance test (Gearhart et al., 2013), quartile deviation (Ab Latif et al., 2017), and inter-rater analysis (Gwet, 2001) were used to evaluate the agreement and concordance of the Delphi rounds. ISM-based analysis (MICMAC) was used to categorise the barriers to provide clarity on the dynamics between elements as done in similar studies (Gift et al., 2023; Saka & Chan, 2020b; Shen et al., 2016).

4. Data analysis

This section presents the data analysis for the collected responses from the Delphi survey panellists.

4.1 Demographic distribution of survey panel

A survey of the Nigerian construction professionals was undertaken to gather information, including experts from varying professions such as designers/architects, developers, contractors, government officials, and academic researchers, which offers robustness and comprehensive insights into the current practices for managing C&D waste in the Nigerian construction sector. In the first round of the Delphi survey, 22 out of 35 targeted experts responded, yielding a response rate of 63%. In the second round, 17% of experts participated, resulting in 49% completing both rounds. The respondents are from diverse backgrounds, with the majority (20/22) having more than five (5) years of experience in the industry (Table A1). About half of the respondents (12/22) have less than five (5) years of CE experience despite having implemented it in projects. This supports the novelty of CE in NCI (Salleh et al., 2022). Out of the 20 experts

invited for the ISM survey, only nine (9) completed the survey, with 67% of experts having more than 11 years of construction experience. 78% of the respondents have at least six (6) years of experience in CE and C&D waste. The minimum academic qualification is a master's degree, with 82% and 78% possessing PhDs in the Delphi and ISM surveys, respectively. Therefore, they are equipped with knowledge and capability to provide relevant data for assessing CE implementation for C&D waste and uncovering the underlying relationships between the implementation barriers.

4.2 Shapiro-Wilk normality test

In the first and second rounds of the Delphi survey, all BRRs have a p-value less than 0.05, which is less than the 0.05 required threshold for normality (Kwak & Park, 2019). Hence, data are said to be not normally distributed. Therefore, non-parametric statistical methods were adopted for further analysis (Aghimien et al., 2018).

4.3 Cronbach alpha reliability test

As shown in Table 2, the Delphi survey's alpha values for the first and second rounds were both over the 0.7 criterion, with the first round recording an alpha value of 0.796 and the second round 0.842. This indicates a close relationship between the variables because it shows significant internal consistency of the instrument (Bland & Altman, 1997; Brown, 2002).

4.4 Kendall concordance test

Kendall concordance coefficient (*W*) values of 0.213 were recorded for the Delphi first round and 0.433 for the second round (Table 2), which are less than the average 0.5. However, Gisev et al. (2013) noted that as the number of respondents grows, it becomes more difficult to get a higher *W* value. As a result, the increase in the *W* value in the successive round, which implies improved consensus, was given consideration. Since there are more than seven attributes, the chi-square value (χ^2) was used as a near approximation (Li et al., 2016). In the second round, χ^2 increased from 89.035 in the first round to 139.931. According to the statistical table, both values are higher than the critical $\chi 2$ of 30.144 at Degree of freedom (df) = 19 and significance (p) = 0.05. Both rounds have an asymptotic significance value of less than 0.001, which is below the 0.005 significance threshold. This reflects both the improvement in the degree of agreement in the second round of the survey and the consistency of expert responses in both rounds (Li et al., 2016).

4.5 Mean score ranking

Having achieved the first objective of the study, which is the identification of the barriers to CE implementation for C&D waste management in construction sector of developing economies via a review

literature (Table 1). Subsequently, the importance level of the identified barriers is evaluated based on the responses from the Delphi survey, addressing the second objective. As shown in Table 2, the mean scores (M.S) and standard deviation values from the two Delphi rounds were used to rank the 20 BRRs. The mean score ranges between M = 3.14 (SD = 1.037) for BRR4 and M = 4.50 (SD = 0.598) for BRR3 in the first round of the Delphi survey. However, BRR8, which ranked second (M = 4.50, SD = 0.673), recorded a lower mean score compared to the first round. It improved, ranking first in the second round of the Delphi (M = 4.47, SD = 0.514), while BRR12, with an initial mean score of M = 3.23 (S.D = 1.193), which ranked 19th, dropped to 20th in the second round with a mean score of M = 2.94 (S.D = 0.659). All the examined barriers are significant, as they have mean values greater than the 2.50 average mean. The ranking revealed pursuit of short-term profitability instead of long-term sustainability (BRR8), insufficient monitoring data about construction waste (BRR3), lack of general understanding of CE opportunities (BRR1), scarce funding and investment opportunities for CE initiatives (BRR5) and lack of obligatory legislation (BRR17) as the most crucial barriers in descending order of criticality, while scarcity of circular and eco-friendly materials (BRR12), complexity of buildings (BRR4) and low economic benefit associated with sorting and recycling (BRR18) were the least ranked barriers.

4.6 Quartile Deviation

In the Delphi first round, nine (9) out of the 20 barriers showed "medium consensus", with QD values > 0.5 or equal to 1. The QD values of the remaining 11 BRRs are < 0.5, indicating a "high consensus" level. As shown in Table 2, all the BRRs in the second round had QD values ≤ 0.5, signifying "high consensus". Hence, in the second round of the survey, experts reached a consensus (Tengan & Aigbavboa, 2021).

Insert Table 2

4.7 Inter-rater analysis (IRA)

IRA statistics (IRA $a_{wg(1)}$) were used to assess and validate the agreement of respondents on each BRR with the level of consensus attained by the experts at each Delphi round (R. D. Brown & Hauenstein, 2005), using interval grading of mean score ≤ 1.5 = Very low; 1.51 to 2.5 = Low; 2.51 to 3.5 = Somewhat high; 3.51 to 4.5 = High; and mean score ≥ 4.51 = Very high, to ascertain the significance grading of each BRR (Zahoor et al., 2017). Table A2 presents the significance grade, $a_{wg(1)}$ score and agreement level for all BRRs. However, the level of agreement of the panellists above the mean borders (i.e., the lower and upper limits) may not be fully reflected in the IRA statistics (Olawumi & Chan, 2019). The mean score boundaries,

M*lower* and M*upper*, are 1.18 and 4.82 for the first round. The M*upper* and M*lower* are 4.76 and 1.24 in the second round, respectively. Results from the analysis suggest a substantial improvement of expert agreement in the second round of the Delphi. The significance grading further reveals a significant impact of the examined barriers to CE implementation for managing C&D waste.

4.8 Interpretive structural modelling (ISM)-based analysis

The structural self-interaction matrix (SSIM), hierarchical structure, and MICMAC were used to examine the relationships between the barriers (Govindan, 2023) which is the focus of the third research objective. To determine the dynamics of the barriers (i and j), the first stage was to input expert responses using the four symbols (V, A, X, and O). V = barrier i influences barrier j; A = barrier j influences barrier i; X = barrier i influences j, and barrier j also influences i; while O = barriers i and j are unrelated.

The SSIM of aggregated expert responses is shown in Table 3. A reachability matrix was developed from the SSIM and then checked for transitivity using a Python function (Saka et al., 2020). The reachability matrix was then partitioned into different levels; a digraph is then developed based on the reachability matrix and hierarchy structure. Lastly, MICMAC was used in categorising the barriers based on their driving and dependence powers.

4.8.1 Structural Self-Interaction Matrix (SSIM)

The notion that "the majority overrules the minority" was applied to the data, as done in similar studies, to prevent subjectivity in the aggregate of the responses (Saka & Chan, 2020b; Shen et al., 2016).

Insert Table 3

4.8.2 Initial reachability matrix

The SSIM is transformed into an initial reachability matrix by substituting binary digits (1 and 0) for V, A, X, and O (Table A3) according to these criteria:

- If entry is V, cell (i, j) equals 1 and (j, i) is 0.
- If entry is A, cell (i, j) becomes 0 and (j, i) is 1.

- If entry is X, both cells (i, j) and (j, i) equal 1.
- Cell (i, j) and (j, i) entries both become 0 if the entry is O.

4.8.3 Final reachability matrix

The final reachability matrix is produced by integrating transitivity into the initial matrix. This fundamental principle of ISM states that if barrier A is linked to barrier B and barrier B to barrier C, then barrier C must undoubtedly be related to barrier A (Attri et al., 2013). This process could be accomplished either by manually checking each variable (BRR) or using loop statements. However, this method is time-consuming and prone to errors. Therefore, a Python function shown below, was used to analyse transitivity in order to guarantee accuracy (Saka & Chan, 2020b).

```
def transitivity (matrix):
    result = ""
    length = len(matrix)
    for i in range(0, length):
        for row in range(0, length):
            for col in range(0, length):
                matrix [row] [col] = matrix [row][col] or (matrix[row][i] and matrix[i][col])
    result += ("\n W" + str(i) +" is: \n" + str(matrix).replace("]," , "] \n") + "\n")
result += ("\n Final Reachability Matrix is \n" + str(matrix).replace("]," , "]\n"))
print (result)
return result
```

Table 4 presents the final reachability matrix for the barriers with the driving and dependence power.

Insert Table 4

4.8.4 Hierarchical structure of the barriers derived from the SSIM

The reachability and antecedent sets of the BRRs are derived from the final reachability matrix. Each iteration of the reachability, antecedent, and intersection set partitions BRRs that share the same intersection set and reachability set to a level. This set of barriers becomes the top-level barrier in the ISM

hierarchy. The levels of the BRRs obtained from Table A4 were used to create the ISM-based hierarchical structure of the 20 barriers, as shown in Figure 2.

Insert Figure 2

4.8.5 Matrice d'Impacts croises-multipication applique a classement analysis (MICMAC)

Using their driving and dependence power (shown in Table 4) and MICMAC, the CE barriers were grouped into four clusters, i.e., autonomous, dependent, linkage, and independent categories. On the y-axis, dependency and driving power have a maximum value of 20 and a minimum value of 1. Consequently, half of the axis is 9.5, and its range is 1 to 20 (19 units). As shown in Figure 3, this splits the boundaries into a two-dimensional pattern (diagraph).

The following explains the four clusters of the digraph:

i. Autonomous cluster: barriers are not connected to the main system, as they have minimal links due to their low dependence and driving power.
ii. Dependent cluster: barriers have a weak driving power but a strong dependence power. Since they rely on associated barriers, these barriers can be overcome through the associated ones.
iii. Linkage cluster: barriers with strong driving and dependent power. They influence other barriers and give feedback on themselves.
iv. Independent cluster: barriers have strong driving power but low dependence power. These are regarded as the most significant barriers in the system.

Insert Figure 3

5. Results and Discussion

5.1 Identification of the barriers to CE implementation for C&D waste (Objective 1)

From existing accounts, 20 distinct barriers to CE implementation for C&D waste management in developing economies ranging from economic, knowledge and awareness, regulatory and supply chain, and technical and resource barriers were identified in this study. The study further situates these barriers within the TOE framework which enables a structured exploration of these barriers from the varying TOE dimension of organisational and technological contexts, which are the components of internal barriers, and environmental context as the sole element of external barrier (Table 1).

5.2 Examining CE implementation barriers for C&D waste management in the NCI (Objective 2)

Analysis revealed that nearly all the barriers are critical to circular C&D waste management in the NCI (Table 2), with 19 out of the 20 barriers having M.S > 3.0 critical threshold on a 5-point Likert scale (Wuni et al., 2022). This demonstrates the relevance of each barrier and their impact in hampering successful CE implementation in Nigeria. The results are subsequently discussed based on the thematic grouping, focusing on the top three critical barriers in each group.

5.2.1 Regulatory and supply-chain barriers

Based on the mean average of each cluster, this category of barriers emerges as the most critical to the implementation of CE practices for C&D waste management in Nigeria (Table 2), aligning with findings from the comparable developing economy contexts of Saudi Arabia (AlJaber et al., 2024), India (Bhavsar et al., 2023; Mhatre et al., 2020) and China (Liu et al., 2021), noting inadequate policy and regulations as a major CE implementation barrier. The emergence of insufficient monitoring data about construction waste (BRR3) as one of the most critical barriers (ranking 2nd overall, 1st in the group) in the NCI echoes the finding of Ogunmakinde et al. (2019) that the construction sector is faced with a poor regulatory framework that incorporates a sustainable waste management approach like CE due to inadequate waste data leading to significant gaps in understanding the scale, composition, and potential for reuse of these waste materials. CE implementation for C&D waste management relies heavily on accurate and comprehensive data to track waste, manage and optimise resource use, and make data-driven decisions for optimal resource management across the value chain (Alite et al., 2023). Therefore, without reliable data, it becomes challenging to make informed decisions and develop policies regarding construction waste reduction, tracking material flow, and recycling demolition waste, further impeding the ability to measure progress towards CE goals and to identify areas where interventions are most needed. Surprisingly, this specific barrier is rarely ranked as a significant CE barrier for C&D waste management in studies from similar contexts. It is therefore essential to establish robust data collection and monitoring systems that can provide accurate insights into waste generation and management practices. This requires investment in technology, adequate government support, and capacity building to ensure that stakeholders across the NCI can collect and analyse waste data effectively.

Additionally, the absence of mandatory legislation that enforces the adoption of CE principles in the NCI (BRR17) impedes CE implementation for C&D waste (ranked 5th overall and 2nd in group). This regulatory gap enables companies to continue with business-as-usual practices without facing any legal consequences, resulting in an uneven playing field, potentially putting companies that opt to adopt CE practices at a competitive disadvantage. This finding is in tandem with Liu et al. (2021), who found that

inadequacy in supportive policies that aid CE adoption and an inadequate legal framework for C&D waste management are the most significant regulatory CE barriers to C&D waste recycling in China, consistently rated as top three barriers. This finding indicates a deficiency in legal and policy frameworks and support to promote effective C&D waste management. Therefore, local contractors should be encouraged by policy to employ recycled materials and products to increase market acceptance and alleviate investor worries.

While the adoption of the CE business model encourages innovative circular business ideas, demonstrating both economic and operational benefits of CE in the practice of developed economies, it assists in overcoming the usual linear production and consumption that hinders CE transition. Lack of circular models to transform BAU practices (BRR6) persists in Nigeria (ranked 7th overall and 3rd in group), indicating that companies are often unsure of how to implement CE strategies in a way that is both economically viable and operationally feasible. Thus, making it challenging for them to understand the potential return on investment from adopting CE practices. For instance, companies investing in sustainable technologies or developing innovative business models that prioritise resource efficiency and waste reduction often face financial constraints due to a lack of existing implementation guidelines, incentives, and government support (Véliz et al., 2023). Therefore, the Nigerian government must continue to collaborate with key stakeholders and financial institutions and actively support CE through policy reforms, legislation, and public education. Likewise, introducing penalties for non-compliance with CE policies is of importance. This would improve CE application within the NCI and boost the overall sustainability of the sector.

5.2.2 Economic barriers

This group of barriers, which ranks second, explains the financial constraints and economic challenges faced by the construction firms in the uptake of CE practices for managing their C&D waste. It includes the lack of funding for novel CE solutions and the poor economic viability regarding the recycling of construction waste materials (Table 2). This theme presents the pursuit of short-term profitability (BRR8), ranking 1st overall, as the most crucial economic barrier. This is not surprising following conclusions from similar developing economy contexts, echoing the findings of Véliz et al. (2023) in Chile and Ding et al. (2023) in China that desire for short-term profitability and client demand for a quick return on investment (ROI) limit the strategic vision of implementing CE for C&D waste. This is because construction firms of developing economies often prioritise immediate financial returns over long-term sustainability due to the nature of the construction business, which is risk-averse (Mahpour, 2018) and largely driven by profit (Babalola & Harinarain, 2024). Even more closely, an earlier study by Suleman et al. (2023) in Nigeria found

demand for a quick ROI by clients as the most critical barrier hindering circular design in Nigeria. Although their study focused on the construction design phase and lacks C&D waste focus. It suggests that the NCI stakeholders, designers especially, lack a clear grasp of CE and its long-term cost-saving benefits. As a result, there is a need for a shift in organisational orientation for CE adoption and its implementation for C&D waste by SMEs within the NCI. Moreover, the current short-sightedness of the NCI regarding sustainability is intensified by economic pressures such as fluctuating material costs and tight project budgets, thereby compelling companies to prioritise cost-saving measures. For instance, most construction firms in Nigeria, SMEs especially, operate within tight profit margins and high capital constraints. The up-front costs associated with setting up recycling facilities and investing in construction techniques with high waste minimisation potential are seen as prohibitive compared to unsustainable linear approaches similar to the Indian construction sector (Mhatre et al., 2020). As a result, decision-makers are typically motivated to minimise immediate cost at the expense of continuous practices that engender waste.

The challenge of funding and investment opportunities for CE initiatives (BRR5), which ranked joint 3rd overall, is the second most crucial economic barrier affecting CE implementation for C&D waste in the NCI. This barrier is, however, not unique to Nigeria but more pronounced in developing economies, as financial ecosystems often lack the maturity to support large-scale investments in sustainability (Huang et al., 2018b). This is because financial institutions are generally risk-averse, particularly when it comes to funding novel initiatives such as CE projects. For example, funding sources, including banks and government grants, typically favour conventional linear construction methods due to their documented profitability, while they exhibit reluctance toward supporting circular efforts that may not yield immediate returns, resulting in a substantial implementation gap (Mhatre et al., 2020). Therefore, without access to capital, construction businesses, particularly SMEs, find it challenging to implement CE practices, which often require upfront investments in new technology, training, and materials management. This economic challenge aligns with Liu et al.'s (2021) finding in China, who found inadequate financial incentive and support as the most crucial economic barrier (ranked 1st) to circular C&D waste management. Although, the cost-intensive nature of deconstruction and recycling processes, which are key aspects of CE, makes it even harder to justify such investments in a financial setting already constrained by limited capital access.

Furthermore, lack of incentives to design construction products for recycling or end-of-life reuse (BRR10) is the third-ranked economic barrier of CE implementation for C&D waste management (ranking 7th overall), as there is little motivation for architects, designers, and contractors to prioritise end-of-life considerations in the design and construction phases. While the NCI has long been driven by cost

minimisation, there is less focus on the recovery of different construction components at the end-of-life for recycling, remanufacture, or trading, which could potentially contribute to financial savings in new construction projects (Eze et al., 2022). This barrier is further exacerbated by the absence of market incentives that reward circular design practices preventing and limiting waste generation. In developed economies, for instance, established frameworks and incentives for companies that incorporate design-for-disassembly or modular construction techniques exist, such as the Eco-design for Sustainable Products Regulation (ESPR) of the European Union, which ease the deconstruction and recycling processes at the end of a building life cycle (Charef et al., 2021). However, the NCI lacks such incentives, leading to the continued dominance of the linear model, where products are designed with little regard for their environmental impact after use. Hence, addressing these crucial economic barriers is important for unlocking long-term value and achieving sustainable growth while promoting circularity in the C&D waste sector of Nigeria and other developing countries.

5.2.3 Knowledge and awareness barriers

These barriers stem from the poor understanding of CE principles and the benefits it offers for C&D waste among the key stakeholders, like designers/planners and contractors, and the broader construction sector. This category of barriers ranks as the third most significant obstacle to effective circular C&D waste management in Nigeria, as shown in Table 2. This contrasts with Wijewansha et al. (2021), who uncovered that lack of knowledge and awareness of CE is the most critical barrier to CE in Sri Lanka, especially in the early phase of construction. Although Sri Lanka and Nigeria share contextual commonalities, current results indicate that the NCI is slowly growing in awareness of CE practices within its C&D waste sector. Result further revealed that stakeholders in the NCI do not have a full and clear grasp of the CE concept, leading to reluctance in adopting its principles and reflecting the risk-averse nature of the industry. Lack of general understanding of CE opportunities (BRR1) therefore, poses a serious roadblock to circular management of C&D waste in Nigeria, as reflected in its ranking (joint 3rd overall and 1st in group). This indicates that relevant stakeholders such as the clients, policymakers, and the public remain unfamiliar with the CE concept and the several economic, environmental, and social value benefits it offers. Hence, changing their perspective from perceiving waste as a disposal problem to a resource is tough, leading to missed opportunities for material recovery, reuse, and recycling, and establishing innovative approaches to repurpose waste streams and divert them from landfills. This finding echoes AlJaber et al.'s (2024) conclusion of a significant lack of awareness of CE principles among key construction stakeholders in Saudi Arabia. In addition to the gap in practice, academic curricula in Nigeria rarely incorporate modules that propagate the understanding of CE principles, resulting in professionals who are not equipped to design and manage projects that minimise waste using circular strategies (Bello & Idris, 2023). Consequently, a

transformative approach is necessary to bridge the knowledge gap and improve CE awareness among the stakeholders to drive its adoption and implementation.

The second critical knowledge and awareness barrier is the limited awareness of CE principles across the CSC (BRR2), ranking 6th overall, which could be correlated to communication gaps among stakeholders from different domains impeding CE proliferation, owing to the fragmented nature of the construction sector and the complex network of actors. This, coupled with the poor communication channels among the key stakeholders across the value chain, including building contractors, developers, suppliers, and demolition contractors, leads to insufficient industry collaboration and prevents knowledge sharing regarding CE, which could promote enthusiasm and build confidence in CE implementation for C&D waste. While effective CE implementation requires coordinated action and shared understanding among the stakeholders, previous research like Charef et al. (2021) demonstrates how stakeholders often operate in silos, focusing on individual benefit without a holistic assessment of the project sustainability, thereby countering the integration of CE practices across the value chain. This lack of standardised guidelines for systematically implementing CE in the CSC to manage its generated waste further compounds the inconsistent application of CE principles (Wu et al., 2022). While suppliers fail to recognise the economic advantages from the recovery and resale of C&D materials, the sheer lack of awareness among them leads to weak demand for recycled and reusable recovered materials. However, with industry-wide platforms and collaborative forums for the dissemination of CE knowledge and innovation, consistency in CE understanding across the CSC could potentially be improved. Consequently, it is essential to educate construction stakeholders on CE and the economic and social potential it holds in addition to the widespread environmental advantages in managing waste from C&D activities and further improve collaboration across the construction value chain for effective and efficient waste management.

The construction industry globally is characterised by a conservative culture and is usually hesitant to depart from the traditional, linear, unsustainable practices and adopt new concepts for efficient and sustainable waste management. In Nigeria, this conservatism is exacerbated by the scepticism towards new and unfamiliar models. This is evident in the reluctance to adopt CE strategies (BRR13), ranking 3rd in this group and 9th overall. The reluctance is underpinned by the lack of awareness and understanding of what CE entails coupled with the associated risks of adopting an unfamiliar concept, thereby making stakeholders resist its adoption and implementation, which further stalls the widespread adoption of CE practices for C&D waste management. Hence, addressing knowledge and awareness barriers requires focused education and targeted campaigns coupled with case studies that demonstrate CE benefits to clear the misconceptions surrounding CE and advance circularity attainment in the Nigerian C&D waste sector.

5.2.4 Technical and resource barriers

This category of CE barriers has the weakest link to the whole system and does not have a severe impact on CE implementation in the NCI. This finding, however, contradicts Bello et al.'s (2024), who found that limited technology capabilities are the most critical barrier hindering CE implementation for the wider Nigerian construction industry. Notwithstanding the absence of C&D waste focus, the study offers crucial insight into current CE practice in the NCI. While all the barriers in this category ranked average and below average (10th to 19th), one of the most significant technical challenges is the inadequate consideration for end-of-life (EoL) issues in the design and construction phases (BRR9), ranking 1st in this group and 10th overall. This emphasises the focus on immediate functional solutions rather than long-term thinking which considers the building's whole life, limiting the progress of CE strategies. For example, the absence of a designer anticipating the dismantling, recovery, recycling, or reuse of materials can significantly impact the potential for waste circularity at the building EoL (Oluleye et al., 2023). This barrier is particularly pressing because integrating EoL considerations is key to the success of CE in minimising C&D waste by prolonging the lifespan of resources through reuse, repair, and recycling. Therefore, to transition effectively to a circular model, the NCI must shift its focus to whole-life building consideration. This barrier also reflects the current challenges to design and construction practices employed in the NCI, which frequently prevent material saving and undermine CE implementation (Torgautov et al., 2021), e.g., construction practices such as poor material procurement, frequent design changes, and inefficient cutting of materials leading to rework and material wastage (Ajayi et al., 2015). Moreover, the construction of complex and non-modular buildings makes deconstruction and material recovery difficult. For instance, once mixed or used in structures, materials like concrete, which is heavily utilised in Nigeria, often prove difficult to repurpose. This shows that designs that do not prioritise flexibility in design for adaptive reuse or dismantling, complicate extended use of building and material and component recovery at the end of a building's life.

Additionally, difficulty in integrating advanced technology into the Nigerian construction sector (BRR7) also poses a challenge, ranking 2nd in the group and 12th overall. Many of the modern technologies that facilitate CE practices, such as Building Information Modelling (BIM), digital material tracking systems, and automated deconstruction tools, are either unavailable, being implemented at a very slow pace, or poorly implemented in Nigeria because of a lack of technical know-how and infrastructure to support these technologies (Eze et al., 2022). Without the ability to track material flows, optimise resource usage, and forecast waste generation, it is exceedingly difficult to implement CE effectively (Akinade et al., 2020).

Thus, while technology integration is essential and driving material sorting, lifecycle assessment, and resource recovery, the Nigerian construction industry remains largely reliant on traditional practices, leading to continuous waste generation.

Furthermore, low value of materials at their end-of-life stage (BRR16) and design practices preventing material savings (BRR19) are also significant challenges, with both ranking 3rd in the group but 15th overall. In a CE, reducing material waste through design is often prioritised in the waste minimisation hierarchy to enable saving of materials and their recovery at the EoL of the structure. However, these innovative practices are lacking within the NCI (Bello & Idris, 2023). Additionally, recycled or repurposed materials post C&D are perceived to hold little value in the market, primarily due to poor material quality, limited processing capabilities, and a lack of demand. The challenge is further compounded by insufficient infrastructure for material recovery and an underdeveloped market for secondary materials. Therefore, addressing these barriers to promote circular C&D waste management requires a systemic shift toward whole-life building design, enhanced technology integration, and development of robust material recovery markets to support CE goals.

5.3 Establishing the interdependencies between CE barriers for C&D waste (Objective 3)

The ISM principle was employed to classify the barriers into partition levels (Figure 2) revealing the interplay of both internal and external CE barriers for C&D waste from the TOE perspective. Level I addresses external and systemic limitations associated with the market environment and innovation adoption. Level II highlights the technical challenges and knowledge gap in adapting CE principles to the construction value chain using digital technologies. Socio-economic and institutional challenges and shortcomings of the current regulations are emphasised in Level III, while Level IV stresses the poor strategic vision and lifecycle thinking of construction assets. These levels highlight the pressing need for structural policy reform and a holistic legislative framework for a successful CE transition. Lastly, Level V presents siloed working practices isolating stakeholders in the construction value chain, ultimately leading to poor collaboration.

The barriers were grouped into independent, autonomous, linkage, and dependent clusters. None of the examined barriers exhibits poor connection to the system (i.e., falls in autonomous cluster). The linkage barriers are BRR1, BRR8, BRR6, BRR5, BRR10, BRR9, BRR13, BRR11, BRR17, BRR16, BRR15, BRR18, and BRR19. Addressing these linkage barriers would influence some other barriers. For example, without understanding the benefits of adopting CE practices in terms of resource conservation, waste reduction and financial savings, there is little or no motivation to make investing in circularity a priority in construction projects. The financial viability of CE initiatives is restricted by the absence of business

models that promote circular practices, which further complicates funding. Additionally, in the absence of defined CE frameworks, construction firms may prioritise immediate profitability, undermining the efforts to transition to circular C&D waste management. The dependent barriers, which are BRR3, BRR2, BRR4, BRR12, BRR20, and BRR7, are best tackled by addressing other associated ones that influence them. This is important for efficient resource allocation and impactful intervention. For instance, when cooperative effort is made within the construction value chain to enhance understanding of CE and its opportunities, it plays a crucial role in addressing the fear and risks associated with the adoption of novel CE initiatives by exchanging information and promoting circularity culture for C&D waste management. Similarly, it encourages system thinking, considering valuable resources that could be reclaimed at the end of a building lifecycle right from the pre-construction phase, addressing the problem of limited reusable and circular materials in Nigerian markets. Lastly, only BRR14 is identified as an independent barrier. Addressing this barrier, which involves collaboration among stakeholders, is crucial for the proliferation of CE practices in sustainable C&D waste management within the NCI. The NCI stakeholders must, therefore, work collectively to coordinate activities, align interests, and share resources to promote circular practices across the construction supply chain to minimise waste generation.

Having discussed the findings on the various barriers impeding CE implementation for C&D waste management in the NCI and drawing on the criticality of the barriers as informed by ranking from experts in the Delphi rounds (second research objective) and underlying interrelationships between the barriers as established by MICMAC (third research objective), a conceptual framework is devised, encapsulating the outcome of the study. It demonstrates an aggregation of the top prioritised CE implementation barriers from each thematic group considering their driving and dependence power, especially the independent (highest driving with minimal dependency power) and the most influential linkage barriers (highest driving and maximum dependency power). Accordingly, enabling measures to mitigate the key barriers are further recommended as presented in Figure 4. This framework will guide both governmental and industry efforts from an emerging economy standpoint towards achieving circularity in the C&D waste sector.

Insert Figure 4

6. Implications, conclusion, and limitations.

6.1 Implications of the study

The study contributed original knowledge to research by offering theoretical and practical implications on the associated barriers to the implementation of CE for C&D waste management in a developing economy

context. While the C&D waste sector poses a significant challenge to sustainable development, existing accounts largely focus on developed countries, limiting the understanding of the unique contextual challenges of CE in emerging economies. Although some studies from developing economies have explored the barriers to CE implementation in the broader construction practice, very few studies within the NCI have empirically assessed their significance with no specific focus on C&D waste. To the best of the authors' knowledge, no previous study has examined the underlying relationships between CE barriers for C&D waste management in the NCI. Hence, this study, while it investigates CE implementation barriers specifically for C&D waste management in a developing economy context framed by the TOE lenses, adopted a pluralistic and iterative Delphi survey approach which seeks consensus of stakeholders to gain a better understanding of the challenges faced in this context. It also advanced knowledge through the examination of the interplay between CE barriers for C&D waste management, offering guidance and further providing solutions to the identified challenges using the ISM approach. Additionally, by utilising ISM to uncover the dependence and influence of the CE barriers, the study contributes to filling a methodological gap in investigating the domain of sustainable C&D waste management in Nigeria.

The outcome of this research will help in tackling the barriers to the implementation of CE for C&D waste management by the government, policymakers, and construction stakeholders in Nigeria and other similar emerging economies struggling to adopt and integrate CE into their construction processes. The hierarchical model offers insights into mitigating these barriers by proposing actionable solutions that prioritise the most influential and critical barriers, subsequently addressing the interrelated barriers, thereby alleviating the dependent and less influential barriers. The suggested enabling measures include the establishment of an integrated regulatory framework for applying CE principles for C&D waste, enhancing collaboration among construction stakeholders across the value chain, and providing financial incentives to construction businesses to encourage the use of recycled and reused materials, as shown in Figure 4.

6.2 Limitations

Despite its contributions, the study encounters some limitations. The present study deviates from the traditional Delphi approach by omitting the initial qualitative round typically dedicated to open-response data. This modification, which was substituted by a critical literature review, was done to reduce the burden of extra rounds on the panellists and streamline the consensus process. This may have constrained the depth of exploratory input from experts at the outset of the Delphi. Therefore, future studies should consider an initial open response round for deeper expert perspectives. Additionally, the proposed ISM model, while helpful, is not statistically validated. Thus, to validate and test the ISM model, future

research may use empirical techniques like Structural Equation Modelling (SEM). Finally, the study is limited with its focus on Nigeria and limited responses from some professions, which prevents even distribution of experts across the panel and could prove as a limitation to the generalisability of the findings. Therefore, while ensuring a more balanced panel, future studies could assess the criticality level of CE barriers and explore their relationships in other infant economies to understand the interconnectedness of the challenges of CE implementation for minimising C&D waste and sustainably managing it.

6.3 Conclusion

This study aimed to investigate the barriers to the implementation of CE strategies for sustainable C&D waste management in a developing economy context, drawing from the lenses of the TOE theoretical framework. Through a Delphi survey and ISM with experts in the NCI, 20 CE barriers were assessed. The findings indicate that while all the barriers are significant ($M \geq 3.0$), the pursuit of short-term profitability, insufficient monitoring data about construction waste, lack of general understanding of CE opportunities, and scarce funding and investment opportunities for CE initiatives are the most crucial barriers to CE implementation in the Nigerian C&D waste sector. However, beyond individual barrier prominence, the group's mean average showed that regulatory and supply-chain barriers collectively outweigh other groups, while technical and resource barriers are the least critical. This indicates a systemic policy and institutional deficiency, thus highlighting the urgent need for robust policy interventions and enforcement mechanisms that support a CE approach to managing C&D waste of the NCI. Additionally, the finding of the study stresses collaborative efforts between the NCI stakeholders and policymakers to promote CE awareness and communicate its financial and sustainability benefits effectively and abate prevailing challenges so as to achieve a sustainable C&D waste sector and also circular construction practices across the industry value chain. Furthermore, the contextual relationships between the barriers were established through MICMAC and the ISM digraph, revealing three (3) distinctive clusters based on their dependence and driving power, which are linkage, dependent, and independent barriers, while the ISM-based hierarchical model determined five (5) partition levels, both offering a very valuable comprehension of the underlying interactions between the barriers and providing a strategic basis for prioritising interventions targeting foundational barriers to drive broader CE integration. In addressing the three research objectives, this study contributes novel empirical evidence on CE barrier prioritisation and their independencies in managing C&D waste in a developing economy setting, advancing theoretical understanding and providing practical guidance for practice. From a practical standpoint, this study advocates for policy reform focused on regulatory reinforcement and financial incentives, alongside capacity building within the NCI. The proposed collaborative efforts seek to stimulate a sustainable

circular construction sector, enhancing resource use and minimising environmental impacts of C&D waste.

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Table 1: Categorisation of the 20 identified barriers of CE implementation for C&D waste (Source: Author's own work)

TOE dimension	Category	Code	Barriers	Sources
Organisational context *(Internal)*	Knowledge and awareness barriers	BRR1	Lack of general understanding of CE and opportunities	(Bhavsar et al., 2023; Ding et al., 2023; Liu et al., 2021; Mahpour, 2018; Wijewansha et al., 2021; Zuofa et al., 2023)
		BRR2	Limited awareness across the supply chain	(Hammadhu & Anjali, 2024; Hentges et al., 2022; Mahpour, 2018; Rahigude et al., 2022; Wijewansha et al., 2021)
		BRR11	Lack of interest	(Papamichael et al., 2023; Zuofa et al., 2023)
		BRR13	Reluctance to adopt CE strategies	(Bhavsar et al., 2023; Karaca & Tleuken, 2024)
		BRR20	Risks associated with adopting new concepts	(Ding et al., 2023; Mahpour, 2018; Torgautov et al., 2021)
	Economic barriers	BRR5	Scarce funding and investment opportunities for CE initiatives	(Bhavsar et al., 2023; Ding et al., 2023; Hammadhu & Anjali, 2024; Karaca & Tleuken, 2024; Liu et al., 2021; Mahpour, 2018; Véliz et al., 2023)
		BRR8	Pursuit of short-term profitability instead of long-term sustainability	(AlJaber et al., 2023; Papamichael et al., 2023; Rahigude et al., 2022; Véliz et al., 2023)
		BRR10	Lack of incentive to design for end of life (products)	(Bhavsar et al., 2023; Mahpour, 2018; Zuofa et al., 2023)
		BRR18	Low economic benefit associated with sorting and recycling	(Bao et al., 2020; Bhavsar et al., 2023)
Technological context *(Internal)*	Technical and resource barriers	BRR4	Complexity of buildings	(Aboginije et al., 2023; Hentges et al., 2022; Mahpour, 2018)
		BRR7	Difficulties in technology integration	(Hentges et al., 2022; Karaca & Tleuken, 2024; Maury-Ramírez et al., 2022; Véliz et al., 2023; Zuofa et al., 2023)
		BRR9	Lack of consideration for end-of-life issues	(Hammadhu & Anjali, 2024; Hentges et al., 2022; Wijewansha et al., 2021)
		BRR12	Scarcity of circular and eco-friendly materials in the market	(Aboginije et al., 2023; Alite et al., 2023; Bao et al., 2020; Hentges et al., 2022; Zuofa et al., 2023)
		BRR16	Low value of material/products at end of life	(Alite et al., 2023; AlJaber et al., 2023; Bao et al., 2020; Mahpour, 2018; Torgautov et al., 2021; Véliz et al., 2023; Wu et al., 2022)
		BRR19	Design and implementation practices that prevent material saving	(Bhavsar et al., 2023; Torgautov et al., 2021)
Environmental context *(External)*	Regulatory and supply chain barriers	BRR3	Insufficient monitoring data for C&D waste	(Costa et al., 2022; Mahpour, 2018; Papamichael et al., 2023; Wu et al., 2022)
		BRR6	Absence of business models that encourage circular practices	(Karaca & Tleuken, 2024; Rahigude et al., 2022)
		BRR14	Lack of collaboration among stakeholders in the industry	(Alite et al., 2023; Bao et al., 2020; Lu et al., 2023; Véliz et al., 2023; Wu et al., 2022)

BRR15	Lack of proper standards of waste management	(Liu et al., 2021; Mahpour, 2018; Maury-Ramírez et al., 2022)
BRR17	Lack of obligatory legislation	(Alite et al., 2023; Bhavsar et al., 2023; Hammadhu & Anjali, 2024; Hentges et al., 2022; Liu et al., 2021; Mahpour, 2018; Papamichael et al., 2023; Silva et al., 2024; Zuofa et al., 2023)

Table 2: Mean score ranking of barriers to CE strategies for C&D waste (Source: Author's own work)

Barriers		First Round						Second Round					
Categories	**Code**	**Mean**	**SD**	**Rank**	**Rank in group**	**QD**	**Group mean's average**	**Mean**	**SD**	**Rank**	**Rank in group**	**QD**	**Group mean's average**
Knowledge and awareness barriers	BRR1	4.23	0.813	6th	2nd	0.50	3.98	4.29	0.588	3rd	1st	0.50	3.93
	BRR2	4.36	0.727	3rd	1st	0.50		4.18	0.636	6th	2nd	0.50	
	BRR11	3.55	1.011	17th	5th	0.50		3.41	0.712	17th	5th	0.50	
	BRR13	4.00	0.816	11th	3rd	0.63		4.06	0.429	9th	3rd	0.00	
	BRR20	3.77	1.066	14th	4th	1.00		3.71	0.588	13th	4th	0.50	
Regulatory and supply-chain barriers	BRR3	4.50	0.598	1st	1st	0.50	4.21	4.47	0.624	2nd	1st	0.50	4.12
	BRR6	4.23	0.612	5th	3rd	0.50		4.12	0.485	7th	3rd	0.00	
	BRR14	3.82	1.006	13th	5th	1.00		3.71	0.686	14th	5th	0.50	
	BRR15	4.14	0.834	9th	4th	0.50		4.06	0.659	10th	4th	0.25	
	BRR17	4.36	0.790	4th	2nd	0.50		4.24	0.562	5th	2nd	0.50	
Economic barriers	BRR5	4.14	0.710	8th	3rd	0.50	4.01	4.29	0.588	3rd	2nd	0.50	4.06
	BRR8	4.50	0.673	2nd	1st	0.50		4.47	0.514	1st	1st	0.50	
	BRR10	4.18	0.795	7th	2nd	0.50		4.12	0.485	7th	3rd	0.00	
	BRR18	3.23	0.973	18th	4th	0.63		3.35	0.702	18th	4th	0.50	
Technical and resource barriers	BRR4	3.14	1.037	20th	6th	1.00	3.62	3.00	0.707	19th	5th	0.50	3.52
	BRR7	3.86	0.834	12th	2nd	0.63		3.82	0.809	12th	2nd	0.50	
	BRR9	4.14	0.889	10th	1st	0.63		4.06	0.659	10th	1st	0.25	
	BRR12	3.23	1.193	19th	5th	1.00		2.94	0.659	20th	6th	0.25	
	BRR16	3.68	1.086	15th	3rd	0.63		3.65	0.606	15th	3rd	0.50	
	BRR19	3.64	0.953	16th	4th	0.50		3.65	0.606	15th	3rd	0.50	
Number of respondents (n)		22						17					
Kendall's coefficient of concordance (W)		0.213						0.433					
Calculated chi square (χ2)		89.035						139.931					
Critical chi square value at p = 0.05		30.144						30.144					
Degree of freedom (df)		19						19					
Asymptotic significance		<0.001						<0.001					

Table 3: SSIM for barriers to CE implementation for C&D waste (Source: Author's own work)

ID	*Bj*																		
Bi	**B20**	**B19**	**B18**	**B17**	**B16**	**B15**	**B14**	**B13**	**B12**	**B11**	**B10**	**B9**	**B8**	**B7**	**B6**	**B5**	**B4**	**B3**	**B2**
B1	V	V	O	A	O	V	O	V	O	X	O	V	V	O	V	V	O	V	V
B2	O	O	O	O	O	O	V	O	O	O	O	O	V	O	V	O	O	V	
B3	O	O	A	O	O	A	O	O	O	A	A	V	O	A	V	A	O		
B4	O	O	O	O	O	O	O	O	O	O	O	V	A	A	O	O			
B5	O	O	A	A	A	O	O	O	O	O	V	V	O	O	A				
B6	O	V	O	A	O	O	V	O	O	A	V	V	A	O					
B7	O	O	O	A	O	O	V	V	V	O	O	O	O						
B8	O	O	A	A	A	O	O	O	V	A	A	A							
B9	O	V	A	A	A	V	O	O	O	A	A								
B10	V	O	O	O	O	O	O	O	O	O									
B11	O	V	O	A	A	A	V	O	V										
B12	O	O	O	A	A	O	O	O											
B13	A	V	A	A	O	A	O												
B14	O	V	O	A	O	A													
B15	O	O	A	A	O														
B16	V	A	O	O															
B17	O	V	O																
B18	V	A																	
B19	O																		

	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12	B13	B14	B15	B16	B17	B18	B19	B20	Drp
B1	1	1	1	1*	1	1	1*	1	1	1*	1	1*	1	0	1	1*	1*	1*	1	1	19
B2	0	1	1	0	0	1	0	1	0	0	0	0	0	1	0	0	0	0	0	0	5
B3	0	0	1	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	3
B4	0	0	1*	1	0	0	1*	0	1	0	0	0	0	0	0	0	0	0	0	0	4
B5	1*	1*	1	1*	1	1*	1*	1*	1	1	1	1*	1*	0	1*	1	1*	1*	1*	1*	19
B6	1*	1*	1*	1*	1	1	1*	1*	1	1	1*	1*	1*	1	1*	1*	1*	1*	1	1*	20
B7	0	0	1	1	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	4
B8	1*	1*	1*	1	1*	1	1*	1	1*	1*	1*	1	1*	0	1*	1*	1*	1*	1*	1*	19
B9	1*	1*	1*	1*	1*	1*	1*	1	1	1*	1*	1*	1*	0	1	1*	1*	1*	1	1*	19
B10	1*	1*	1	1*	1*	1*	1*	1	1	1	1	1	1	0	1	1*	1*	1*	1	1	19
B11	1	1*	1	1*	1*	1	1*	1	1	1*	1	1	1	1	1	1*	1*	1*	1	1*	20
B12	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1
B13	1*	1*	1*	1*	1*	1*	1	1*	1*	1*	1*	1*	1	0	1	1*	1*	1*	1	1*	19
B14	1*	1*	1*	1*	1*	1*	1	1*	1*	1*	1*	1*	1*	1	1	1*	1*	1*	1	1*	20
B15	1*	1*	1	1*	1*	1*	1*	1*	1*	1*	1*	1	1*	0	1	1*	1*	1*	1*	1*	19
B16	1*	1*	1*	1*	1*	1*	1*	1	1	1*	1*	1	1*	0	1*	1	1*	1*	1*	1	19
B17	1	1*	1*	1*	1	1	1	1	1	1*	1	1	1	1	1	1*	1	1*	1	1*	20
B18	1*	1*	1	1*	1	1*	1*	1	1	1*	1*	1*	1	0	1	1*	1*	1	1*	1	19
B19	1*	1*	1*	1*	1*	1*	1*	1*	1*	1*	1*	1*	1*	0	1*	1	1*	1	1	1*	19
B20	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	2
Dpp	14	15	18	16	14	16	16	15	16	14	14	16	15	5	14	14	14	14	14	14	

Note: * – Transitive values; Dpp – dependence power; Drp – driving power

Table 4: Final reachability matrix for CE barriers (Source: Author's own work)

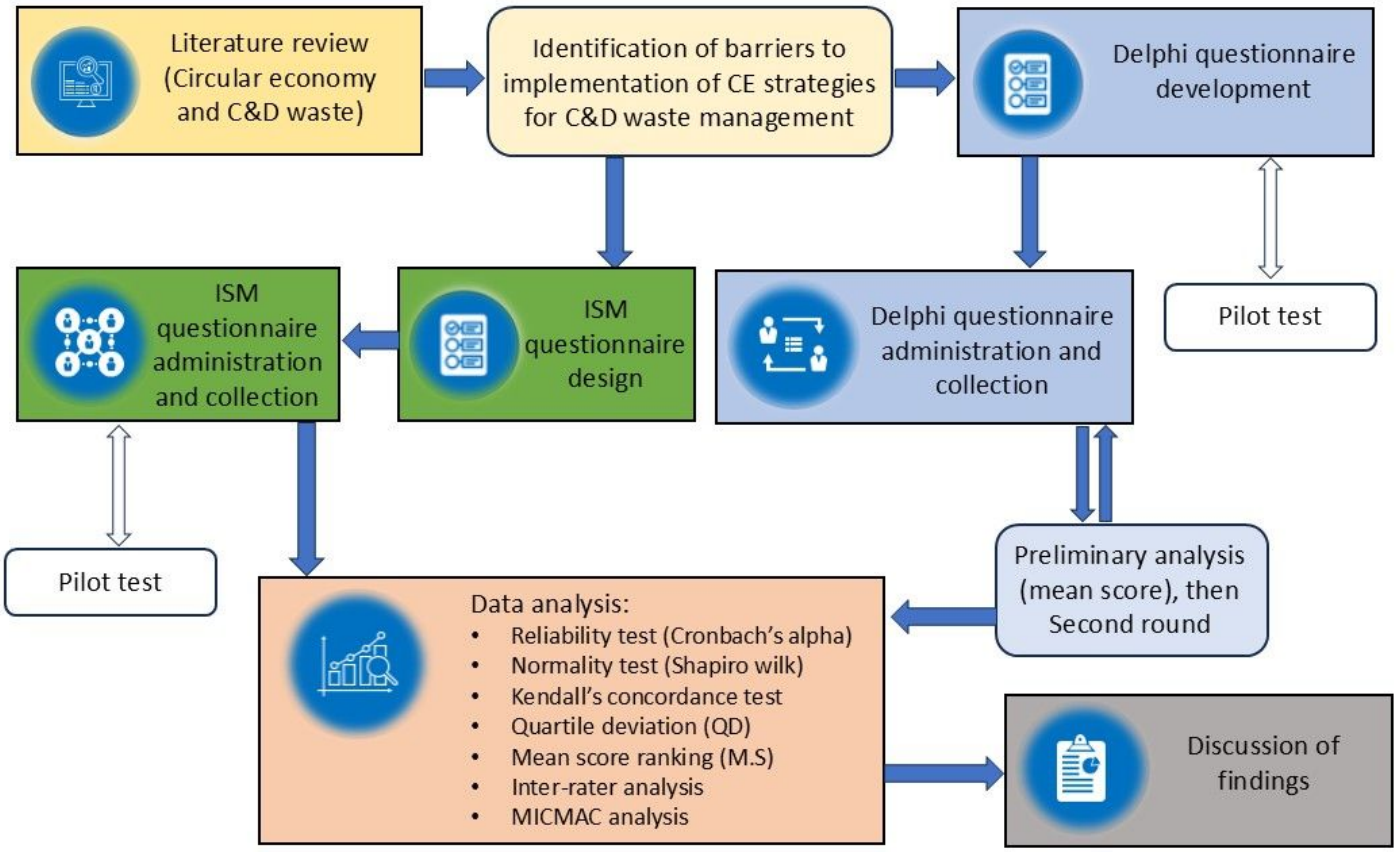

Figure 1: Overall research plan for the study (Author's own work).

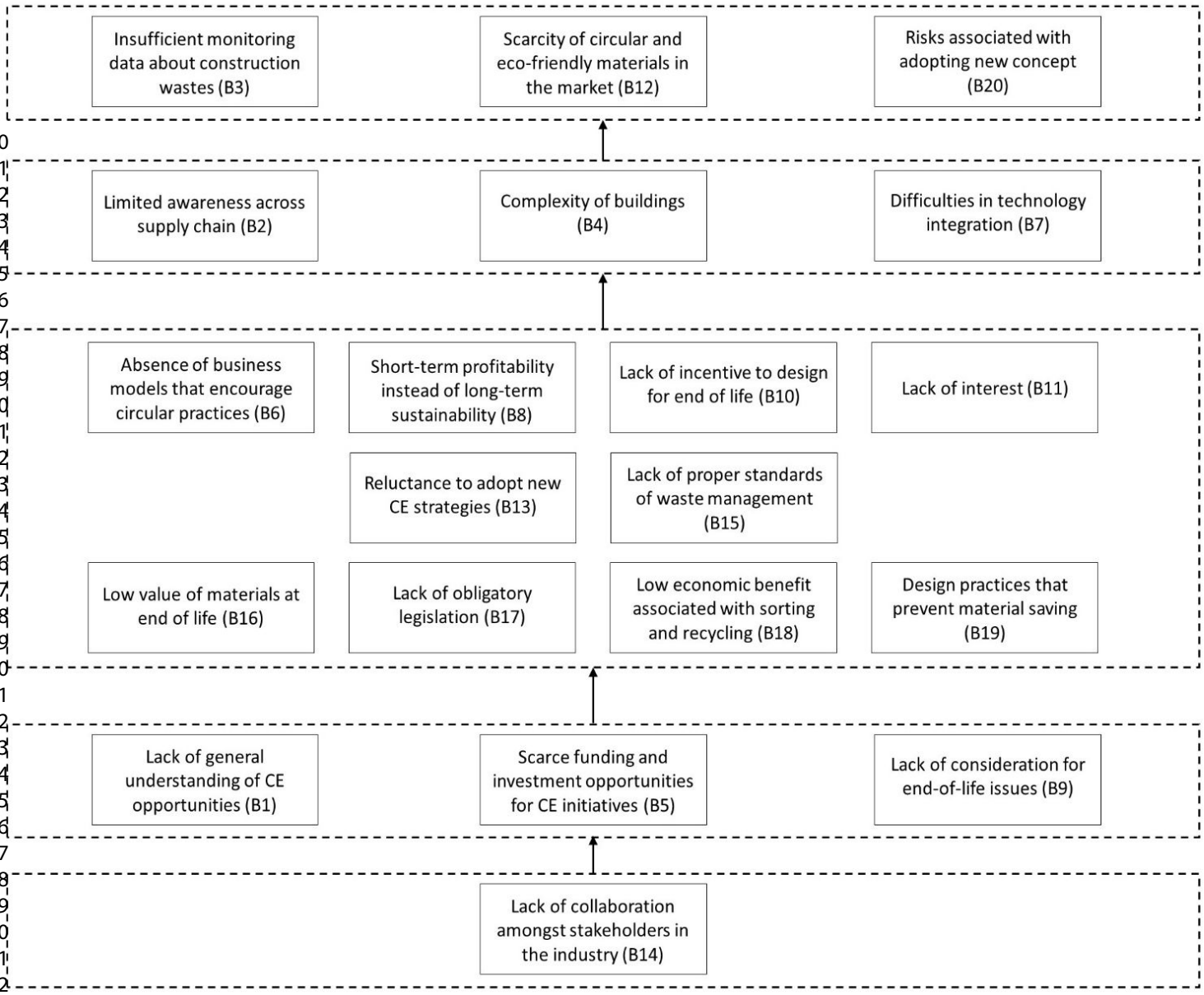

Figure 2: ISM model for barriers to implementation of CE strategies for C&D waste (Author's own work)

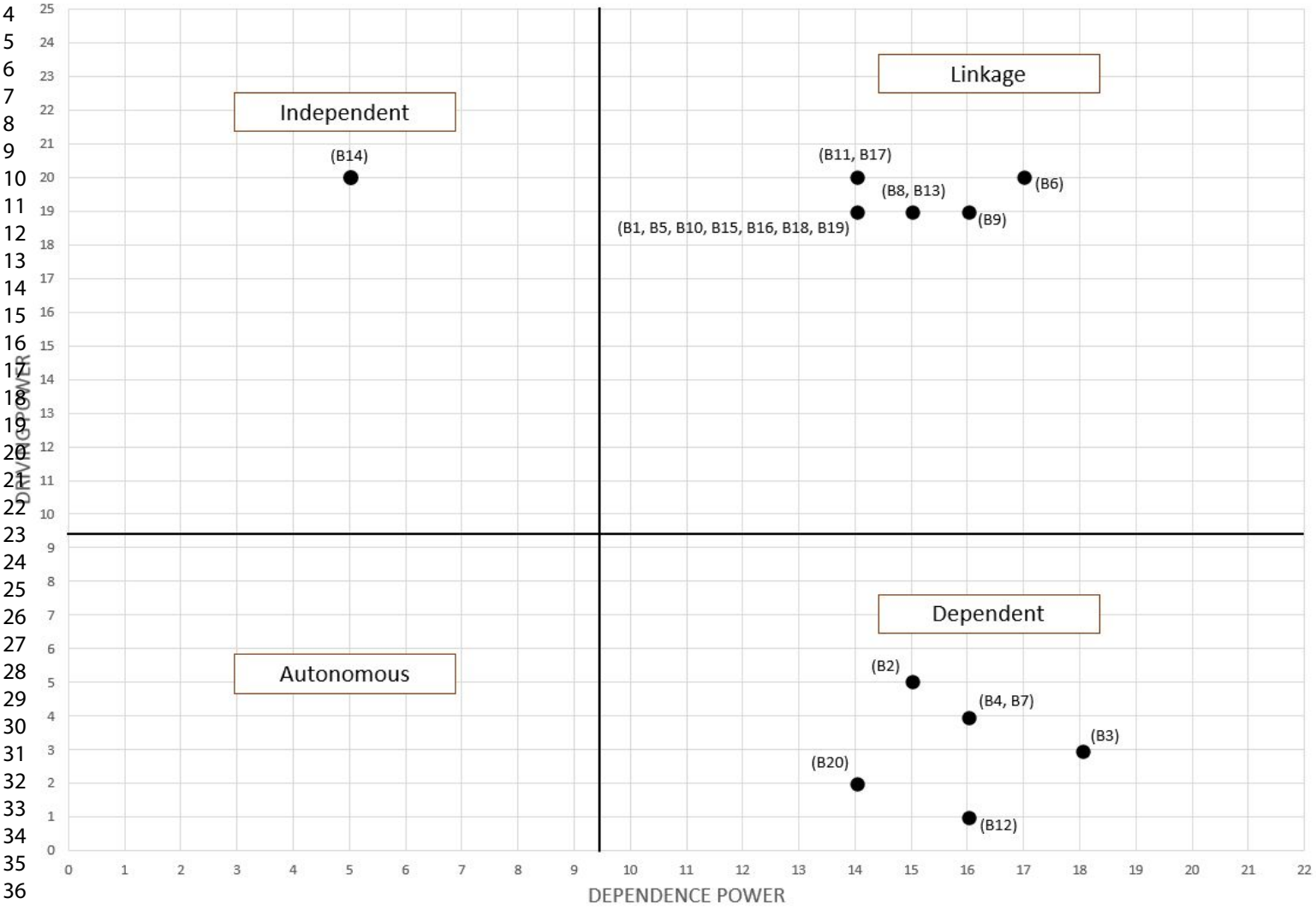

Figure 3: Digraph and MICMAC analysis of barriers to implementation of CE strategies for C&D waste (Author's own work)

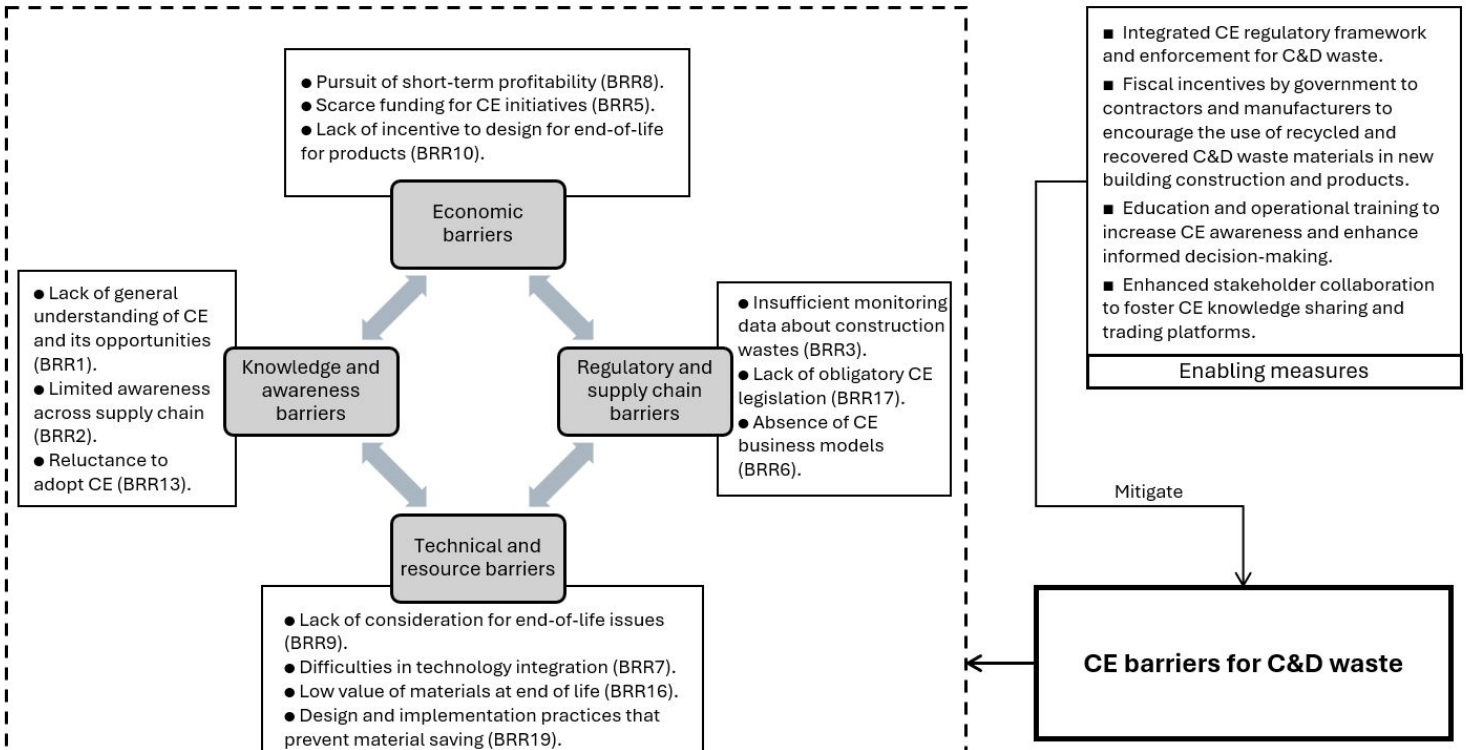

Figure 4: Conceptual model of CE implementation barriers for C&D waste and mitigating actions (Author's own work).

Journal Name: ***Construction Innovation: Information, Process, Management***

Manuscript Title: **Investigating Circular Economy Barriers for Construction and Demolition Waste in the Construction Industry: A Delphi and Interpretive Structural Modelling Approach**

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Summary Sheets to Specific Comments from the Editor and Reviewers

The authors wish to thank the editor and the two anonymous reviewers for their time and efforts in reviewing our manuscript. We hope that the responded changes listed below have made the manuscript suitable for publication and we look forward to your early responses.

Associate Editor(s)' and Reviewer(s)' Comments to Author: **Reviewer: 1**	**Authors' Responses to Comments from Editor**
Recommendation: Minor Revision Comments: (There are no comments.) Additional Questions: 1. Originality: Does the paper contain new and/or significant information adequate to justify publication?: The study presents a context-specific analysis tailored to the Nigerian setting, which enhances its originality and relevance within that locale. However, the generalisability of its findings to other developing countries is limited, as the supporting information on these contexts lacks sufficient rigour and depth. 2. Relationship to Seminal Literature: Does the paper demonstrate an adequate understanding of the relevant literature in the field and cite an appropriate range of literature sources? Is any significant work ignored?: The discussion on barriers to Circular Economy (CE) implementation lacks comprehensiveness, as previously noted. Furthermore, it is unclear whether the discussion pertains to	The authors appreciate the editors and the reviewers for taking the time to further review the work to improve the content and ensuring meaningful contribution to the wider research community. 1. Comments are very well noted with thanks. The generalisability of the study findings to other developing economies has been highlighted in the conclusion (Line 746 - 753) and introduction sections of the work (Line 78 & 84 - 85). 2. Well noted with thanks. (a) The literature review has been extensively improved. The discussion of CE barriers for C&D waste is now strictly focused on emerging economies to provide deeper contextual understanding of the challenges. This is evident in the heading of the literature discussion (Section 2.1: Line 94) and its content (Line 97 – 102;

global barriers or is limited to those specific to developing countries. Clarifying this scope is essential for contextual accuracy. It would also strengthen the study to highlight the significance of further analysis into the importance and interrelationships of these barriers, as this would directly support the stated research questions. Additionally, the inclusion of both Figure 1 and Table 1—each presenting CE implementation barriers—appears redundant. It is recommended to consolidate this information into a single, well-structured Table 1, incorporating the content of Figure 1 along with appropriate justifications	Line 107 - 112). (b) The old figure delineating the identified barriers to the TOE framework has been removed, while Table 1 has been consolidated to include the information from the deleted figure to avoid redundancy. A section of the literature review signposting the reader to the new table and providing brief description is included in Line 124 – 127.
3. Research Methodology: Is the paper's argument built on an appropriate base of theory, concepts, or other ideas? Has the research or equivalent intellectual work on which the paper is based been well designed? Are the methods employed, robust, defendable and appropriate?: The information provided on the research methodology is generally adequate. However, it would be beneficial to include the specific selection criteria used for purposive sampling, particularly in relation to how participants were identified as experts. This addition would enhance the transparency and credibility of the sampling process.	3. Comment well received and appreciated by the authors. The predetermined criteria for selecting research participants have been included in the methodology section as advised. (Line 220 - 228).
4. Results: Results: Are results presented clearly and analysed appropriately? Do the conclusions adequately tie together all elements of the paper?: -While the data analysis section is informative, many of the detailed tables could be moved to the appendix, retaining only the key outcomes in the main body of the paper to improve readability and focus. -Regarding Figure 5, it is unclear how this conceptual framework was derived. Specifically, it is not evident whether the barriers included were selected based on their importance or another criterion. A more detailed explanation of the rationale behind the development of the framework is necessary. Additionally, the framework currently appears somewhat disconnected from the core focus of the paper, which may confuse readers. Clarifying its relevance and alignment with the research objectives would strengthen the overall coherence of the study. -Section 5.2 appears to be repetitive, as much of its content has already been discussed in Section 5.1. It is recommended to merge the overlapping content into a single, cohesive section to avoid redundancy and improve the flow of the discussion.	4. Comments are well noted. (a) Former Table 3 (Significance grading and IRA analysis of barriers to CE) has been moved to the supplementary list (A2). (b) The rationale and relevance for developing the conceptual framework (figure 4) have been included in the work with justification of the included barriers (Line 674 - 680) while the framework itself has been modified to ensure focus on the research aim. The implication of the framework is also included in the same paragraph (Line 681 - 682). (c) First, the discussion section of the work has been improved while the contents of the former Section 5.2 have been incorporated Section 5.1 to consolidate the discussion and enhance the flow of the discussion as suggested (Line 444 – 445; 456 – 457; 465 – 470; 489 – 495; 519 – 521).

5. Implications for research, practice and/or society: Does the paper identify clearly any implications for research, practice and/or society? Does the paper bridge the gap between theory and practice? How can the research be used in practice (economic and commercial impact), in teaching, to influence public policy, in research (contributing to the body of knowledge)? What is the impact upon society (influencing public attitudes, affecting quality of life)? Are these implications consistent with the findings and conclusions of the paper?: The conclusion currently reads more like a summary of findings rather than a critical synthesis. It should be strengthened by providing more rigorous conclusions that clearly reflect the implications of the findings, address the research questions, and highlight the contribution to knowledge and practice. Consider also including recommendations for future research and practical applications. Since you have already included the implications separately, maybe you can revisit the section for better clarity.	5. Feedback well received and appreciated by the authors. (a) Although Section 6.1 explicitly discuss the theoretical and practical implications of the study, the conclusion section has been reviewed to include the corrections and clarity (Line 734 – 737; 738 – 742; 746 - 753), while some of the highlighted contents are not entirely new additions, they have been revised to improve the work. (b) Recommendation for further research is already included after highlighting the limitations of the current study (Line 723 - 726).
6. Quality of Communication: Does the paper clearly express its case, measured against the technical language of the field and the expected knowledge of the journal's readership? Has attention been paid to the clarity of expression and readability, such as sentence structure, jargon use, acronyms, etc. Do the figures/tables aid the clarity of the paper?: The overall quality of the paper can be substantially improved by addressing the comments outlined above. Enhancing clarity, reducing redundancy, and aligning the discussion and conclusion more closely with the research objectives will significantly increase the paper's academic rigour and impact	6. Comment well noted. The results of the study are currently discussed based on the research objectives. The three objectives are each addressed in Section 5.1, 5.2, and 5.3. As earlier stated, the conclusion section of the work has been extensively improved based on the feedback from (5) and also (6).

Thank you again for your time and efforts, and for helping us in improving the manuscript.