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Mega-Projects in Construction: Barriers in the Implementation of Circular Economy Concepts in the Kingdom of Saudi Arabia

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Abstract: The construction sector has been subjected to scrutiny due to its propensity for waste generation and the extensive utilisation of finite natural resources. In response to these concerns, a transition towards a novel conceptual framework known as circular economy (CE) has been advocated. Nevertheless, the integration of CE principles within the construction domain encounters numerous impediments to its advancement. Despite scholarly recognition of these challenges, scant research has been devoted to elucidating the intricacies associated with the planning and execution of large-scale projects, particularly within developing nations such as the Kingdom of Saudi Arabia (KSA). This paper intends to fill this gap through the identification and ranking of those barriers encountered when trying to implement CE during construction in KSA. To this end, a comprehensive literature review was completed, alongside a survey conducted amongst 239 participants involved in three mega-projects. A statistical analysis of the data collected was carried out based on the one-way analysis of variance (ANOVA). Following this, a relative importance index (RII) was established to rank 24 barriers categorised as major within the sample. The findings revealed the lack of regulation within the construction sector, the lack of education and training, little awareness and guidance on the subject, and the absence of an incentives policy as primary barriers to adopting CE in KSA. The present study endeavours to enhance the comprehension regarding the principles of circular economy (CE) and the attendant challenges encountered during its implementation. The overarching objective is to provide insights that can inform decision-making processes, thereby facilitating the development of robust mitigation strategies and the adoption of best practices.

Keywords: circular economy (CE); CE barriers; construction; mega-projects

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1. Introduction

The construction sector significantly contributes to the global domestic product (GDP), surpassing 11% [1]. However, the multifaceted activities associated with this sector have deleterious environmental ramifications. Widely recognised as a substantial consumer of natural resources, the construction industry utilises over one-third of globally extracted raw materials [2]. Moreover, criticism has been directed towards its substantial waste generation, accounting for approximately 25% of solid waste generated worldwide [2], while also contributing to approximately one-fifth of total pollutant emissions [3]. These circumstances underscore the imperative for transitioning away from the prevailing linear economic model, characterised by the take–make–dispose approach to industrialised products, towards the adoption of a circular economy (CE) framework. CE is described as "a system where materials never become waste and nature is regenerated..." [1]. Such a paradigm shift aims to reincorporate end-of-life materials and products into a sustainable economic loop, mitigating environmental impacts and fostering resource efficiency. This transition is imperative to fostering more sustainable preservation of resources, therefore minimising the generation of waste [2,3].

Circular economy has various definitions; amongst these, the one given by Amudjie et al. [4] refers to it as a closed-loop system that mitigates material and energy scarcity challenges and fosters more sustainable economic models. According to Kirchherr [5] and Munaro and Tavares [6], CE promotes the reduction, reuse, and recycling of the materials and resources to maintain the use of resources over an extended period.

Despite the recognised benefits of CE in construction projects, the concept is still in its infancy and requires further study. Although barriers to implementing circular economy have been investigated in both developed and developing countries, the focus has been generic, i.e., addressing small-, medium-, and large-scale constructions. This research therefore aimed to distinguish these from each other and focus, in the present investigation, on different types of mega-projects being built in Saudi Arabia, the reason being that mega-projects require substantial costs, much larger scope–impact–risk, and involvement by stakeholders [7].

In Saudi Arabia, the construction sector contributes to approximately 6% of the GDP and offers over 3 million jobs [8]. The adoption of circular economy principles is pivotal for the country's economy, and is in fact at the core of its 2030 development vision. As evidenced by a study conducted by Ouda et al. [9], less than 14% of construction waste in Saudi Arabia is currently reused or recycled. This highlights opportunity areas for our engineering practice in KSA, in terms of detecting constraints to CE in construction mega-projects and finding solutions that support the country's development objectives.

A thorough understanding of the barriers to implementing CE in construction mega-projects holds significance not only for advancing the field of construction engineering but also for supporting Saudi Arabia and similar countries in their pursuit of sustainable development goals. This study aims to identify and priorities the barriers to CE in KSA's construction sector based on surveys. This approach enables us to directly interact with stakeholders engaged in three selected case studies (mega-projects), named Project A (building), Project B (urban development), and Project C (infrastructure).

The study is divided into six sections. Section 1 provides an overview of circular economy and the importance of the study in the context of Saudi Arabia. Section 2 provides a comprehensive literature review of CE's definition and interpretations, its implementation in the construction industry, and the barriers associated with that process. Section 3 outlines the methodology adopted for this study. Section 4 presents the findings and Section 5 presents an in-depth discussion on the results. Finally, Section 6 provides some final remarks and recommendations for future study.

2. Literature Review

2.1. Concept of Circular Economy

The potential of circular economy (CE) to reduce material waste while contributing to the Sustainable Development Goals (SDGs) is sparking significant interest amongst stakeholders [10–12]. Furthermore, CE plays a primary role in advancing the green economy, which strategically aims to reduce carbon emissions and use resources efficiently [13]. Scholars offer a range of interpretations for the CE paradigm. In their examination of 114 definitions of CE, Kirchherr et al. [5] note that several of these definitions focus on the financial and ecological aspects, overlooking community considerations. Notably, these definitions are often guided by the 3Rs principle: reduce, reuse, and recycle. Ellen MacArthur Foundation [2] provides the following definition of CE: "restorative and regenerative industrial system, by intention and design. It replaces the 'end-of-life' concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models". This quotation underscores the importance of using renewable energy source and minimising waste.

Likewise, Amudjie et al. [4] highlight that the establishment of a closed-loop system can foster a more sustainable economic model and deliver ecological and social benefits. Furthermore, Kirchherr et al. [5] describe CE as "economic system that is based on business models which replace the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes, [. . .], with the aim to accomplish sustainable development, which implies creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations". This definition reaffirms the premise that, in nature, waste is a non-existent concept, as the output from one process serves as the input for another. This highlights CE core purpose: to minimise waste generation, reduce emissions, and optimise product benefits by reusing, recycling, and recovering materials at the end of their life cycle [14,15].

2.2. Circular Economy in the Construction Industry

The construction sector continues with the linear economy's inertia, despite its accompanying challenges, although awareness is being raised around the benefits it could generate by shifting towards circularity [16]. Furthermore, the increasing adoption of environmental, social, and governance (ESG) principles highlights their crucial role in advancing sustainability practices within the industry [17,18], enabling construction organisations to contribute to the development of circular economy.

Implementing CE strategies in the construction sector promises numerous benefits, including but not limited to cost reduction, environmental preservation, and the enhancement of societal well-being [10,16,19,20]. Furthermore, CE can play a vital role in contributing to the sustainability in the sector [20]. According to Pomponi and Moncaster [21], circular construction involves elements/systems that extend their lifespans and reduce waste. By prioritising flexibility, durability, disassembly, and deconstruction, a continuous flow of materials is ensured across construction lifecycle stages [22–24].

While the World Economic Forum report primarily focuses on productivity, it underscores the positive impact of circular economy on construction, through enhancing sustainability and resource efficiency. The report demonstrates that every 1% reduction in construction costs is accompanied by a 30% reduction in energy consumption, saving approximately USD 100 billion annually [25]. This illustrates the significance of circular practices in mitigating environmental impacts and optimising resource usage. Yet, significant barriers that impede the broader adoption of CE principles in the construction industry exist [6].

2.3. Barriers to Implementing Circular Economy

Although circular economy offers numerous benefits, its implementation faces various challenges, as highlighted in [3,6,26]. These challenges are crucial for improving the application of CE principles; therefore, researchers endeavour to prioritise key constraints that affect developed and developing countries. The most common barriers impeding the successful implementation of circular economy in various EU countries including Belgium, the Netherlands, the United Kingdom, Denmark, and Italy relate to inadequate legislation and technology [27]. This highlights a regional nuance, i.e., despite the common goal, different nations demand tailored strategies and policies for effective implementations.

In the United Kingdom, Adam et al. [28] investigated the adoption of and main barriers to implementing CE in the building industry. Their study revealed challenges such as a lack of incentives, limited stakeholder awareness/interest, and supply chain-related issues as primary obstacles that emphasises the key role of regulatory frameworks and financial incentives driving the adoption of CE. Similarly, Akinade et al. [29] found similar obstacles: insufficient legislation, a lack of guidance and knowledge, economic and market immaturity, and tool-related issues.

In the United States, Rios et al. [30] investigated CE challenges at the design stage. They highlighted limitations around project performance, legislation, and technical standards, while arguing that these hinder reuse and recovery as well as the absence of CE knowledge. The study suggests strategies based on leadership, education, integration, and contractual expertise to foster CE principles. Likewise, a separate study conducted in the US, Pacific Northwest, identified regulatory constraints, market issues, building codes, design philosophies, lack of awareness, and education on CE principles as the most significant barriers [31]. Similar constraints have been highlighted by researchers in France [32] and Australia [33], whose remarks expand on the need for better stakeholder coordination, regulations, and incentives.

According to Bilal et al. [34], developing countries find the lack of regulation, government support, and little public awareness as the main hindrances to the progression of CE. Additionally, Torgautov et al. [35] note deficiencies in CE skills, high implementation costs, inadequate regulations, and a lack of awareness as primary barriers to implementing circular economy in Kazakhstan. In Lagos, Nigeria, a study conducted by Suleman et al. [36] proposes raising awareness and introducing supportive regulatory measures and incentives to further promote CE principles.

The research highlighted above converges on the idea that circular economy barriers in the building sector are consistent across developed and developing countries, especially concerning legislation and awareness-related factors. However, in developing countries, the affordability of adopting CE in mega-projects is a prominent issue. Despite the state of the art on the subject, further research is required to fully understand the nature and complexity of CE barriers in construction mega-projects and enable us to formulate solutions. Table 1 summarises the barriers encountered through the literature review (referenced) for implementing CE.

Table 1. Barriers to circular economy implementation in the construction industry.

Code	Barrier	Reference
B1	Lack of circular economy regulation and laws.	[3,6,26,27,29–33,35,36]
B2	Low taxation of raw materials and disposal fees.	[3,6]
B3	Absence of incentive policy for material and product circulation and reuse.	[3,6,26,28,32,33,36]
B4	Lack of national strategic targets with clear indicators for circular economy implementation.	[6,26,36]
B5	Limited support for circular economy research and innovation.	[6]
B6	High price of secondary materials compared with that of virgin materials.	[6,26,35,36]
B7	Relatively high costs of investment in waste technology.	[6,27,32]
B8	Insufficient budget for construction waste management.	[35]
B9	Cost of circular economy implementation.	[3,6,28,30,35,36]
B10	Limited availability of secondary market.	[3,6,28,29,31,36]
B11	Absence of relevant stakeholder commitment to waste minimisation and circular economy implementation.	[3,26,28,31,36]
B12	Less preference for and trust in the quality of secondary materials.	[29,35]
B13	Absence of successful examples that provide evidence of benefits of circular economy implementation.	[3,26]
B14	Limited technical codes on circular economy implementation.	[6,26,29,31,32,35]
B15	Lack of circularity consideration in the design stage.	[3,28–32]
B16	Absence of quality standards of reused materials and lack of certification.	[3,6,26,29,30,35]
B17	Lack of effective waste and secondary material management plan in terms of collection and sorting out at site.	[6,29]
B18	Lack of capable and economically viable recycling treatment.	[35,36]
B19	Lack of stakeholder awareness and understanding of circular economy and its impacts.	[3,6,26,28,32,33,35,36]
B20	Lack of education and training in circular economy principles.	[3,30–32,36]
B21	Poor skills related to waste reduction and circular economy implementation.	[3,30,32,33,35]
B22	Lack of accurate and reliable data on construction waste.	[3,6,29,35,36]
B23	Lack of database that complies with design software BIM.	[6,26,29,35,36]
B24	Absence of clear and precise indicators to monitor, control, and measure circularity adoption.	[3,32,36]

3. Methodology

3.1. Research Design and Data Collection

The implementation of circular economy in Saudi Arabia is still in its early stages. To tackle this problem, our study attempts to identify the main barriers to fully implementing CE in construction mega-projects in Saudi Arabia. This is carried out via an extensive literature review designed to interpret and simplify CE's various definitions and barriers to its implementation; see Table 1. A questionnaire was developed to collect data representing opinions and perspectives from professionals involved in three construction mega-projects in KSA.

The first draft of the referred questionnaire was peer-reviewed by 3 academic professors and 16 industry professionals with 8 to 21 years of experience in the construction and building sector. Their feedback was key to ensuring clarity and eliminating ambiguity. Furthermore, this group of professionals participated in refining the initially identified barriers through an extensive literature review. Consequently, some barriers were combined with others due to overlapping issues. This process resulted in 24 barriers, each confirmed for its theoretical and practical importance.

The concept of CE was introduced to the participants in the beginning to ensure the clarity of the term, especially for those who might not gave been aware of it. The questionnaire was divided into two sections. The first section contained background information (such as the project name, participant's position, experience, and education level). The second section listed the identified barriers to implementing circular economy in construction, based on the literature review reported above. A 5-point Likert scale (i.e., 1 = strongly disagree; 2 = disagree; 3 = moderate; 4 = agree; 5 = strongly agree) was proposed for each barrier to capture participants' perceptions of each barrier. Furthermore, a five-point Likert scale was used to facilitate the data analysis of the questionnaire via close-ended questions. The data were analysed via Statistical Package for Social Science Analysis (SPSS) software (version 29) and further processed in MS Excel (version 16.81).

One-way ANOVA was used to identify significant differences among the three construction mega-projects. Moreover, Pearson's correlation was used to investigate the relationship between barriers. Following this, the relative importance index (RII) was used to rank the barriers for implementing CE. The index given in Equation (1) has been used in previous studies to categorise awareness and barriers [34,37]:

$$\text{Relative Importance Index(RII)} = \frac{\sum \text{w}}{\text{AN}} \tag{1}$$

where:

w = Weight assigned by participants to each barrier.
A = Maximum weight (5-; the 5-point Likert scale in this study).
N = Total number of participants (239 in this study).

This method of quantifying the relative importance through the RII can provide a clear and comparative measure of each barrier, facilitating a systematic approach to identifying the most significant barriers to CE adoption. It is used in this study as it offers a direct comparison between multiple barriers in the three mega-projects.

3.2. Sample and Population

The questionnaire was tailored to professionals who have been involved in three case studies, each characterised by their substantial scale and investment. Project A involves a complex of both commercial and residential buildings that cover a vast area with a budget of more than USD 6 billion. Project B is an expansive urban development initiative, also with a budget exceeding USD 5 billion. Project C is focused on infrastructure, with a USD 3 billion budget, emphasising large-scale improvements and expansions that are essential for supporting the region's growth. The participants were the professionals working on-site and in office settings, ranging from directors and project managers to engineers. The sample was selected to provide greater insight into the barriers to implementing

CE practices. The participants were selected using a convenience sampling approach based on their willingness and accessibility. Project A, B, and C are classified as mega-projects according to the criteria outlined by Ashkanani and Franzoi [38] and Flyvbjerg [7]. Each project is characterised by its complexity: extended schedules which exceed five years, large construction areas, and significant risks and associated impacts.

The formula by Yamane [39] was used to estimate the sample size, as follows:

$$n = \frac{N}{1 + N(e)^2} \tag{2}$$

where

n = The sample size.
N = The population size.
e = The confidence level (1-confidnece percent).

Applying Equation (2) while considering a 95% confidence level and a population size of approximately 567 yielded the minimum required sample size of 235.

An invitation email containing a link to a Google Form was sent to targeted professionals in the three mega-projects, requesting their participation in the study. To achieve the minimum required sample, the survey was distributed to 345 professionals. From the 247 responses received, 8 were excluded because the participants' positions (HR managers and public relations employees) were weakly related to construction activities. As a result, the number of valid responses was set to 239, which resulted in a response rate of 69.28%. This response rate exceeds that observed in similar studies within the field of construction and civil engineering, such as those cited in Bilal et al. [34] and Fathalizadeh et al. [40].

To ensure the authenticity and reliability of the response, the following different steps were taken:

Verification process: at the beginning of the survey, the participants were asked about their positions, the name of the project, and their role in the organisation.

Confidentiality of the participants: Both in the sent email and in the introduction of the survey, the confidentiality of the responses was assured. This measure was taken to encourage honesty and minimise bias, supporting these by assuring that the purpose of the survey was for research only.

Data cleaning and validation: As part of the data validation process, the survey was designed to prevent the submission of incomplete responses. Furthermore, additional data cleaning was performed, resulting in the exclusion of 8 responses.

3.3. Reliability Test

The reliability of the data was statistically tested via Cronbach's alpha coefficient (α), which ranges from 0 to 1. A higher value indicates stronger internal consistency and reliability of the data. A Cronbach's alpha coefficient (α) of 0.7 or higher is considered an acceptable value [41,42]. The Cronbach's alpha coefficient (α) is calculated using the equation below [43]:

$$\alpha = \frac{K}{K-1} * (1 - \frac{\sum \delta i^2}{\delta x}) \tag{3}$$

where

α = Cronbach's alpha coefficient.
K = Number of items.
$\sum \delta i^2$ = Sum of variance of each item.
δx = Total variance of all scores.

The reliability of the CE barriers was tested in two stages in this study. Firstly, a pilot study involving a subset of participants from the three mega-projects resulted in a Cronbach's alpha coefficient (α) of 0.937, indicating exceptional internal consistency. This step was crucial to ensure the validity and reliability of the survey at an early stage. After that, the main study yielded a Cronbach's alpha coefficient (α) of 0.922. This demonstrates consistency and allows us to label the data as reliable and suitable for progressing our study.

3.4. Data Normality

The normality analysis integrates various methods, including Kolmogorov–Smirnov (K-S), skewness and kurtosis, a visual examination of a histogram, and a Q-Q plot. The K-S test did not yield significant results (p = 0.200), whereas both skewness (−0.179) and kurtosis (−0.430) results suggested that the distribution did not significantly deviate from normal. This is visually supported by the histogram in Figure 1, which shows a distribution that is relatively symmetrical around the central score. Furthermore, the Q-Q plot in Figure 2 confirms normality as most data points lie on the diagonal line, indicating only minor deviations.

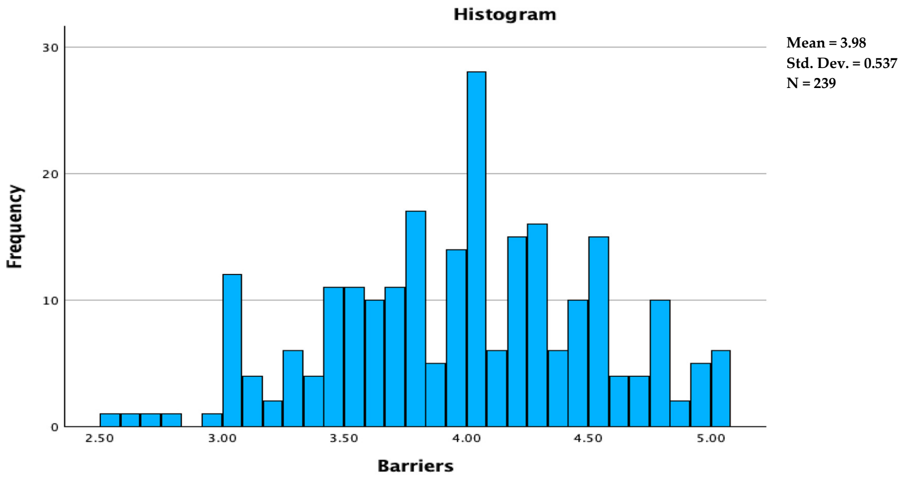

Figure 1. Histogram of circular economy barriers.

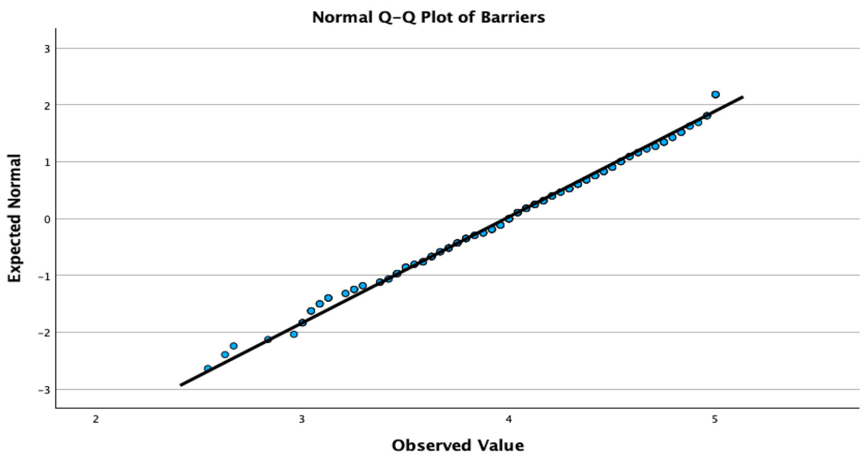

Figure 2. Q-Q plots of circular economy barriers.

In light of these findings, parametric tests were then used. The parametric tests use the results of the K-S test, skewness and kurtosis, histogram, and Q-Q Plot, which overall suggest that the data are nearly normally distributed. Therefore, parametric tests are adopted for the scrutiny of CE barriers in construction mega-projects due to the compatibility of the data.

The opinion of the participants across the three projects differed based on the distinct nature of each project. It was thus essential to retrieve the 24 CE barriers to determine if there were statistically significant differences across the selected projects. To achieve this, the parametric test ANOVA was used to compare CE barriers between the three construction mega-projects. If significant differences were observed, further tests were conducted to identify contrasting group clusters.

4. Results

We define barriers to CE implementation as the reasons why the new economic paradigm has not been fully implemented in the targeted construction mega-projects. The evidence to support our judgement is based on descriptive and inferential results obtained with Statistical Package for Social Sciences (SPSS) and Microsoft Excel. The data were examined using one-way ANOVA and Pearson's correlation, and categorised based on the relative importance index (RII).

4.1. The Demographic Profile

The breakdown of the sample of respondents to our survey was as follows: Project A (36.4%), Project B (33.9%), and Project C (29.7%). The final sample reflects a sound balance across the participants' positions and years of experience, which fulfils our objective for providing a good sense of the market. The professional roles of participants cover design engineers (13.0%), HSE engineers (3.3%), MEP engineers (7.9%), procurement engineers (2.9), project directors (2.1%), project managers (27.2%), quality engineers (12.1%), quantity surveyors (7.1%), and site engineers (24.3%).

In terms of work experience, participants with less than 5 years of experience represented 27.2% of the sample. The other participants had 6–10 years (24.7%), 11–15 years (20.5%), and above 15 years (27.6%) of experience. This diversity helps us to understand the research problem from multiple perspectives. Finally, with regard to educational level, participants with bachelor's and master's degrees constituted 77.8% and 22.3% of the sample, respectively. Figure 3 provides a summary of the participants' demographic information.

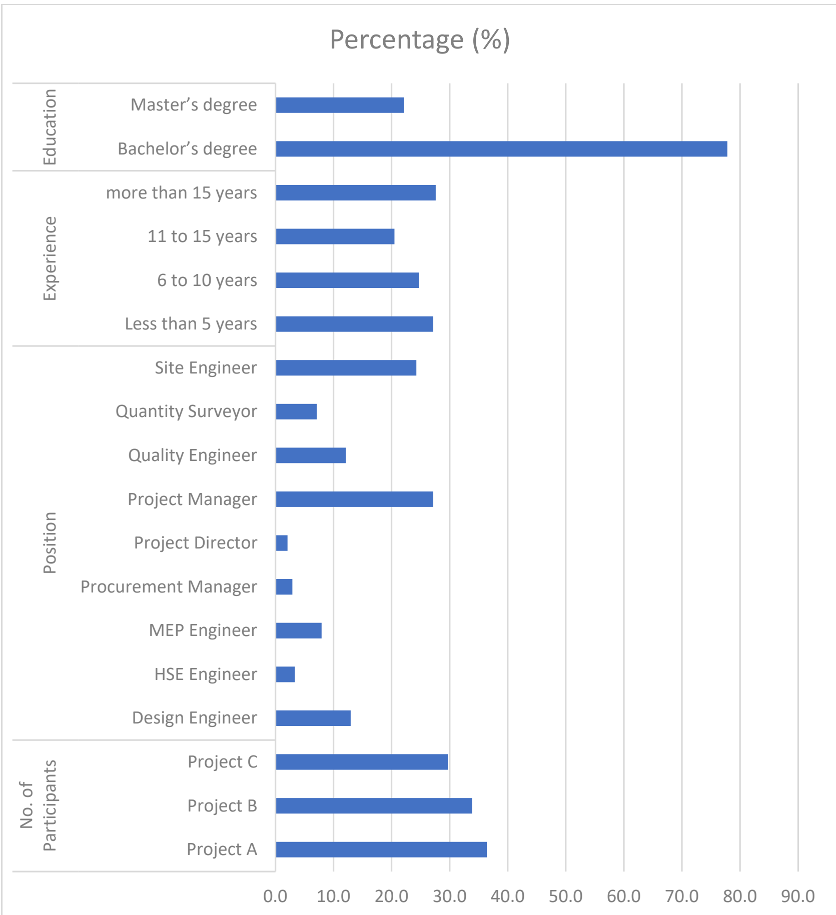

Figure 3. Demographic information of the participants.

4.2. Descriptive Analysis

Descriptive analysis provides a summary of data and helps us to understand their basic features. Table 2 represents the descriptive analysis of the dataset on the barriers to circular economy in the three construction mega-projects. The variables were categorised under the codes B1 through B24, and each code had corresponding data points for “Strongly Agree” (SA), “Agree” (A), “Moderate” (M), “Disagree” (D), and “Strongly Disagree” (SD), along with the mean and standard deviation for each barrier.

Table 2. Descriptive analysis results of the barriers to implementing circular economy in the three construction mega-projects.

Code	SD	D	M	A	SA	Mean	Standard Deviation
B1	2	3	45	90	99	4.18	0.84
B2	9	33	79	85	33	3.42	1.01
B3	3	7	42	85	102	4.15	0.90
B4	3	4	45	101	86	4.1	0.85
B5	2	9.0	46	102	80	4.04	0.87
B6	13	27	66	77	56	3.57	1.13
B7	1	24	72	83	59	3.73	0.96
B8	5	23	66	97	48	3.67	0.97
B9	5	18	51	114	51	3.79	0.94
B10	3	12	48	104	72	3.96	0.90
B11	3	5	51	102	78	4.03	0.86
B12	6	9	51	101	72	3.94	0.94
B13	0	9	47	86	97	4.13	0.86
B14	1	12	40	98	88	4.09	0.88
B15	2	8	45	105	79	4.05	0.85
B16	2	13	45	97	82	4.02	0.91
B17	2	7	52	96	82	4.04	0.87
B18	0	12	46	102	79	4.04	0.85
B19	2	9	38	94	96	4.14	0.88
B20	1	5	40	98	95	4.18	0.81
B21	2	6	51	98	82	4.05	0.86
B22	1	10	42	94	92	4.11	0.87
B23	2	9	45	100	83	4.06	0.87
B24	0	8	41	103	87	4.13	0.81

Observing the mean scores, it is clear that there was general agreement between the statements related to each code. The highest mean score observed was 4.18, for B1, “regulation and laws”, and B20, “education and training”, which suggests a strong level of agreement. However, the lowest mean was 3.42 for B2, “Low taxation of raw materials”, indicating moderate agreement overall.

The standard deviation gives an insight into the variability of the responses. Higher standard deviation values, like 1.01 for B2, “Low taxation of raw materials”, suggest the variability in opinions among the responses, whereas a lower value, such as 0.81 for B20, “education and training”, suggests that the responses were more consistent in terms of agreement.

4.3. ANOVAs

The ANOVA test was used to examine the statistical differences between our target projects. The results of this analysis are shown in Table 3 in terms of the sum of squares, degrees of freedom, mean square, F-statistic, and significance values.

Table 3. ANOVA test results of the barriers to implementing circular economy in the three construction mega-projects.

		Sum of Squares	df	Mean Square	F	Sig.
B1	Between Groups	0.670	2	0.335	0.476	0.622
	Within Groups	165.949	236	0.703		
	Total	166.619	238			
B2	Between Groups	1.062	2	0.531	0.516	0.598
	Within Groups	243.097	236	1.030		
	Total	244.159	238			
B3	Between Groups	0.384	2	0.192	0.235	0.791
	Within Groups	192.888	236	0.817		
	Total	193.272	238			
B4	Between Groups	0.497	2	0.249	0.343	0.710
	Within Groups	171.093	236	0.725		
	Total	171.590	238			
B5	Between Groups	0.388	2	0.194	0.256	0.775
	Within Groups	179.193	236	0.759		
	Total	179.582	238			
B6	Between Groups	0.410	2	0.205	0.160	0.852
	Within Groups	302.201	236	1.281		
	Total	302.611	238			
B7	Between Groups	0.511	2	0.255	0.276	0.759
	Within Groups	218.351	236	0.925		
	Total	218.862	238			
B8	Between Groups	1.232	2	0.616	0.650	0.523
	Within Groups	223.655	236	0.948		
	Total	224.887	238			
B9	Between Groups	0.212	2	0.106	0.120	0.887
	Within Groups	207.906	236	0.881		
	Total	208.117	238			
B10	Between Groups	0.698	2	0.349	0.425	0.655
	Within Groups	193.963	236	0.822		
	Total	194.661	238			
B11	Between Groups	0.281	2	0.140	0.189	0.828
	Within Groups	175.452	236	0.743		
	Total	175.732	238			
B12	Between Groups	1.651	2	0.826	0.926	0.398
	Within Groups	210.408	236	0.892		
	Total	212.059	238			
B13	Between Groups	0.152	2	0.076	0.102	0.903
	Within Groups	175.563	236	0.744		
	Total	175.715	238			
B14	Between Groups	0.338	2	0.169	0.218	0.804
	Within Groups	182.817	236	0.775		
	Total	183.155	238			

Table 3. *Cont.*

		Sum of Squares	df	Mean Square	F	Sig.
B15	Between Groups	0.514	2	0.257	0.351	0.705
	Within Groups	172.884	236	0.733		
	Total	173.397	238			
B16	Between Groups	0.255	2	0.128	0.153	0.858
	Within Groups	196.640	236	0.833		
	Total	196.895	238			
B17	Between Groups	0.360	2	0.180	0.237	0.789
	Within Groups	179.222	236	0.759		
	Total	179.582	238			
B18	Between Groups	0.202	2	0.101	0.138	0.871
	Within Groups	172.459	236	0.731		
	Total	172.661	238			
B19	Between Groups	0.008	2	0.004	0.005	0.995
	Within Groups	183.155	236	0.776		
	Total	183.163	238			
B20	Between Groups	0.056	2	0.028	0.042	0.959
	Within Groups	156.564	236	0.663		
	Total	156.619	238			
B21	Between Groups	0.205	2	0.102	0.139	0.871
	Within Groups	174.088	236	0.738		
	Total	174.293	238			
B22	Between Groups	0.086	2	0.043	0.057	0.945
	Within Groups	179.863	236	0.762		
	Total	179.950	238			
B23	Between Groups	0.463	2	0.232	0.302	0.739
	Within Groups	180.717	236	0.766		
	Total	181.180	238			
B24	Between Groups	0.088	2	0.044	0.066	0.936
	Within Groups	156.146	236	0.662		
	Total	156.234	238			

The results across the three projects reveal a similarity in the perception of the professionals regarding the barriers to circular economy implementation. Moreover, it can be observed that all p-values exceeded the threshold (p-value > 0.05). This indicates that there are no significant differences between the circular economy barriers among the three projects. This indicates that the construction mega-projects (A, B, and C) share nearly identical barriers to circular economy, and these are not affected by project type.

4.4. Correlation Analysis for Circular Economy Barriers in Construction Mega-Projects

The barriers of circular economy in construction mega-projects were analysed using Pearson's correlation to determine the strength and existence of relationships between them. Tables 4 and 5 show the results of Pearson's correlation test. All values of Pearson's correlation in the table are positive and range from 0.056 to 0.728, indicating varying degrees of linear association between the barriers.

Table 4. Results of Pearson's correlation test between CE barriers.

Code	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12	B13
B1	--												
B2	0.156 **	--											
B3	0.504 **	0.237 **	--										
B4	0.336 **	0.161 **	0.353 **	--									
B5	0.273 **	0.190 **	0.351 **	0.399 **	--								
B6	0.312 **	0.144 *	0.339 **	0.199 **	0.289 **	--							
B7	0.232 **	0.142 *	0.413 **	0.245 **	0.316 **	0.464 **	--						
B8	0.263 **	0.248 **	0.303 **	0.168 **	0.255 **	0.391 **	0.360 **	--					
B9	0.220 **	0.121 *	0.204 **	0.212 **	0.358 **	0.367 **	0.419 **	0.514 **	--				
B10	0.336 **	0.137 *	0.301 **	0.328 **	0.344 **	0.268 **	0.221 **	0.425 **	0.453 **	--			
B11	0.296 **	0.095	0.270 **	0.255 **	0.398 **	0.275 **	0.220 **	0.270 **	0.354 **	0.488 **	--		
B12	0.216 **	0.085	0.219 **	0.212 **	0.321 **	0.121 *	0.246 **	0.238 **	0.366 **	0.386 **	0.458 **	--	
B13	0.294 **	0.056	0.326 **	0.206 **	0.246 **	0.242 **	0.304 **	0.204 **	0.313 **	0.217 **	0.335 **	0.306 **	--
B14	0.357 **	0.081	0.355 **	0.197 **	0.398 **	0.234 **	0.328 **	0.231 **	0.320 **	0.311 **	0.381 **	0.372 **	0.402 **
B15	0.358 **	0.126 *	0.400 **	0.190 **	0.394 **	0.271 **	0.289 **	0.288 **	0.403 **	0.481 **	0.513 **	0.385 **	0.335 **
B16	0.277 **	0.1	0.339 **	0.199 **	0.446 **	0.267 **	0.295 **	0.317 **	0.356 **	0.461 **	0.429 **	0.515 **	0.233 **
B17	0.192 **	0.190 **	0.292 **	0.177 **	0.337 **	0.362 **	0.261 **	0.285 **	0.347 **	0.323 **	0.308 **	0.249 **	0.268 **
B18	0.291 **	0.176 **	0.332 **	0.192 **	0.350 **	0.389 **	0.285 **	0.360 **	0.237 **	0.373 **	0.331 **	0.296 **	0.315 **
B19	0.344 **	0.084	0.450 **	0.201 **	0.450 **	0.207 **	0.280 **	0.233 **	0.324 **	0.425 **	0.490 **	0.386 **	0.270 **
B20	0.375 **	0.217 **	0.532 **	0.145 *	0.389 **	0.308 **	0.325 **	0.292 **	0.249 **	0.364 **	0.395 **	0.305 **	0.388 **
B21	0.268 **	0.138 *	0.452 **	0.212 **	0.443 **	0.312 **	0.315 **	0.224 **	0.267 **	0.399 **	0.455 **	0.348 **	0.316 **
B22	0.256 **	0.123 *	0.380 **	0.241 **	0.383 **	0.247 **	0.203 **	0.288 **	0.288 **	0.406 **	0.445 **	0.295 **	0.295 **
B23	0.297 **	0.172 **	0.368 **	0.253 **	0.413 **	0.239 **	0.220 **	0.285 **	0.278 **	0.381 **	0.440 **	0.224 **	0.292 **
B24	0.296 **	0.166 **	0.439 **	0.195 **	0.333 **	0.271 **	0.319 **	0.277 **	0.196 **	0.293 **	0.368 **	0.258 **	0.398 **

**. Correlation is significant at the 0.01 level (1-tailed). *. Correlation is significant at the 0.05 level (1-tailed).

Table 5. Results of Pearson's correlation test between CE barriers (continued).

Code	B14	B15	B16	B17	B18	B19	B20	B21	B22	B23	B24
B15	0.488 **	--									
B16	0.456 **	0.513 **	--								
B17	0.354 **	0.405 **	0.456 **	--							
B18	0.355 **	0.419 **	0.509 **	0.532 **	--						
B19	0.437 **	0.641 **	0.507 **	0.378 **	0.392 **	--					
B20	0.374 **	0.552 **	0.456 **	0.413 **	0.507 **	0.679 **	--				
B21	0.425 **	0.537 **	0.517 **	0.438 **	0.424 **	0.644 **	0.694 **	--			
B22	0.395 **	0.491 **	0.523 **	0.355 **	0.516 **	0.497 **	0.609 **	0.602 **	--		
B23	0.372 **	0.459 **	0.528 **	0.374 **	0.483 **	0.511 **	0.526 **	0.575 **	0.728 **	--	
B24	0.410 **	0.361 **	0.367 **	0.428 **	0.456 **	0.418 **	0.503 **	0.536 **	0.499 **	0.548 **	--

**. Correlation is significant at the 0.01 level (1-tailed).

The strongest correlations (Pearson's correlation coefficient of 0.728) are between (B22) "lack of accurate and reliable data on construction waste" and (B23) "Lack of database that complies with design software, BIM". These correlations are significant at the 0.01 level (1-tailed), indicating a strong positive relationship and high statistical significance. This suggests that the absence of a database that complies with BIM is strongly associated with a lack of construction waste data in the context of the barriers to circular economy in construction mega-projects. It implies that challenges with BIM integration can significantly impact the ability to monitor and measure the effectiveness of circular economy practices.

The second most significant relationship was observed between (B20) "Lack of proper education and training of circular economy principles" and (B21) "Poor skills related to waste reductions and circular economy implementation", with a Pearson's correlation coefficient of 0.694. This indicates the need for educational programs to develop the necessary competencies for circular economy practices. Furthermore, the third strong relationship is between (B19) "Lack of stakeholders' awareness and understanding of circular economy and its impacts" and (B20) "Lack of proper education and training of circular economy principles", with a Pearson correlation coefficient of 0.679. This demonstrates the importance of raising awareness through education and training.

Furthermore, the Pearson's correlation coefficient of 0.644 between (B21) "Poor skills related to waste reductions and circular economy implementation" and (B19) "Lack of stakeholders' awareness and understanding of circular economy and its impacts" highlights a significant interdependency. This strong correlation indicates that enhancing stakeholders' awareness is likely to contribute positively to the development of the skills needed for implementing CE principles.

On the other hand, the weakest relationship was observed between (B2) "Low taxation of raw materials and disposal fees" and (B13) "Absence of successful examples that provide evidence of the benefits of circular economy implementation", with a Pearson correlation coefficient of 0.056. This indicates a very weak positive correlation and lacks statistical significance.

The aforementioned findings underscore the need to enhance BIM integration, training, education, and awareness among stakeholders to overcome the circular economy barriers in the construction mega-projects.

4.5. Relative Importance Index (RII)

The RII was used to quantify and rank barriers for the entire dataset and for each project. By fragmenting the data, the existence of differences in ranking across the projects could be assessed. Subsequently, the RII for the entire dataset provided broader insights into the barriers to circular economy in construction projects, irrespective of the project type or nature.

4.5.1. Cross Comparison of CE Barriers across Target Projects

Table 6 shows the results of the RII ranking across Projects A, B, and C. These results confirm outputs generated with other methods, as reported above. For example, B20, "Lack of proper education and training of circular economy principles", consistently emerges as a primary barrier in projects A, B, and C (RII = 0.83908, 0.832099, and 0.833803, respectively), noting that in Project C, the most significant barrier is B1, "Lack of circular economy regulation and laws" (with RII = 0.850704). Based on these results, we could state that education and training are key for the adoption of circular economy practices in the construction mega-projects. In contrast, B2, "Low taxation of raw materials and disposal fees", is identified as the least impactful barrier, as it receives the lowest RII scores (0.701149, 0.671605, and 0.676056) and maintains a consistent rank of 24 across the three projects.

Table 6. Ranking of circular economy barriers across three construction mega-projects.

Code	Project A		Project B		Project C	
	RII	**Rank**	**RII**	**Rank**	**RII**	**Rank**
B1	0.832184	2	0.824691	3	0.850704	1
B2	0.701149	24	0.671605	24	0.676056	24
B3	0.829885	3	0.822222	4	0.842254	2
B4	0.827586	6	0.807407	8	0.825352	7
B5	0.811494	15	0.797531	13	0.816901	11
B6	0.724138	22	0.711111	23	0.704225	23
B7	0.754023	20	0.750617	21	0.732394	22

Table 6. *Cont.*

Code	Project A		Project B		Project C	
	RII	Rank	RII	Rank	RII	Rank
B8	0.714943	23	0.745679	22	0.743662	21
B9	0.751724	21	0.765432	19	0.75493	20
B10	0.77931	19	0.795062	17	0.805634	18
B11	0.809195	16	0.797531	13	0.814085	12
B12	0.804598	18	0.765432	19	0.791549	19
B13	0.829885	3	0.819753	6	0.830986	4
B14	0.82069	9	0.807407	8	0.825352	7
B15	0.813793	12	0.797531	13	0.819718	10
B16	0.809195	16	0.795062	17	0.808451	15
B17	0.813793	12	0.797531	13	0.814085	12
B18	0.813793	12	0.8	11	0.808451	15
B19	0.829885	3	0.82716	2	0.828169	6
B20	0.83908	1	0.832099	1	0.833803	3
B21	0.818391	11	0.804938	10	0.808451	15
B22	0.825287	7	0.817284	7	0.825352	7
B23	0.82069	9	0.8	11	0.814085	12
B24	0.822989	8	0.822222	4	0.830986	4

We must recognise that the results highlighted above cannot be labelled as universal. For instance, Barrier B1, "Lack of circular economy regulation and laws", is ranked as the most significant in Project C, ranked second in Project A, and ranked third in Project B, reflecting some divergence. Likewise, Barriers B3, "Absence of incentive policy for material and product circulations and reuse", and B24, "Absence of clear and precise indicators to monitor, control, and measure the circularity adoption", demonstrate high levels of significance (with RII values over 0.82 in both), although their ranks vary between projects, suggesting a context-dependent perception of their impact.

4.5.2. Ranking of Circular Economy Barriers in Construction Mega-Projects

Table 7 provides a comprehensive analysis of the circular economy barriers in construction mega-projects and ranks them according to the relative importance index (RII), irrespective of the project type. The primary barriers that have were identified are B1, "Lack of circular economy regulation and laws"; B20, "Lack of proper education and training of circular economy principles"; B3, "Absence of incentive policy for material and product circulations and reuse."; and B19, "Lack of stakeholders' awareness and understanding of circular economy and its impacts" (RII = 0.835146, 0.835146, 0.830962, and 0.828452, respectively). These findings underscore the regulatory framework and standards, education programs, and incentive initiatives as the top-ranked barriers to CE transition.

B13, "Absence of successful examples" (RII = 0.826778), B24, "Absence of clear and precise indicators to monitor, control, and measure the circularity adoption" (RII = 0.825105), and B22, "Lack of accurate and reliable data on construction waste" (RII = 0.822594), are ranked accordingly, indicating the absence of circularity legislations, reliable data on waste quantities, and demonstrable construction examples. These barriers prevent stakeholders from implementing circularity practices. Therefore, the existence of laws and regulations, along with accurate data on waste in the construction sector, is essential to facilitate the transition to circular economy practices. Additionally, establishing an example of circular construction contributes to this transition and minimises waste disposal.

Table 7. Ranking of circular economy barriers in construction mega-projects.

Code	RII	Rank	Code	RII	Rank
B1	0.835146	1	B13	0.826778	5
B2	0.683682	24	B14	0.817573	9
B3	0.830962	3	B15	0.807531	13
B4	0.820084	8	B16	0.804184	17
B5	0.808368	12	B17	0.805858	15
B6	0.711297	23	B18	0.805021	16
B7	0.746444	21	B19	0.828452	4
B8	0.733891	22	B20	0.835146	1
B9	0.757322	20	B21	0.810879	11
B10	0.792469	18	B22	0.822594	7
B11	0.806695	14	B23	0.811715	10
B12	0.787448	19	B24	0.825105	6

The remaining barriers are ranked in Table 7. This table provides valuable insights for policymakers and governmental agencies to develop necessary legislation and incentives to mitigate those barriers. Additionally, stakeholders and organisations can play a pivotal role in reducing these barriers by raising awareness and providing education initiatives.

5. Discussion

Although the circular economy concept has been recognised as an essential approach for waste reduction, resource optimisation, and sustainability, its implementation faces various challenges [3,6]. Despite recent efforts to prioritise and identify the barriers within building and the built environment, there remains a worldwide knowledge gap in identifying and prioritising the barriers within construction mega-projects. To address this gap, this study aimed to identify the most significant barriers to CE implementation. Drawing from previous works, 24 barriers were identified and incorporated into the survey conducted across three construction mega-projects in Saudi Arabia. The responses from 239 professionals across Project A, "building", Project B, "urban development", and Project C, "infrastructure", were collected and ranked using the RII to assess the level of concern regarding CE barriers across these projects.

While examining the three construction mega-projects, this study revealed an intriguing result: the participants across the three projects highlighted similar concerns regarding the top seven barriers across the three projects regardless of their ranking within each project, except for B24, which ranked eighth in Project A. This consistency demonstrates a shared perspective among the participants across the projects on the importance of the top seven barriers to CE implementation. Similarly, an analysis of the bottom-ranking barriers (from 18 to 24) exhibited consistent rankings across the projects, which reflects their limited impact on these barriers to implementing CE. However, overall, there was slight variation in the ranking of CE barriers across the projects, which might be attributed to differences in project nature and type.

In the analysis of the CE barriers, the respondents from the three mega-projects held the following point of view on the most significant barriers to implementing CE in Saudi Arabia: "regulation and laws", "education and training", "absence of incentive policy", "stakeholders' awareness", "absence of successful examples", "precise indicators to monitor the circularity adoption", and "Lack of accurate and reliable data on construction waste".

The lack of regulation and the absence of education programs are considered the top barriers in this study. The establishment of a regulatory framework can facilitate the adoption of CE principles in the sector, which is in line with the findings of similar studies conducted in both developed and developing countries [32,33,36]. Likewise, there is a need for targeted programs to enhance knowledge and equip professionals with the necessary skills to implement circularity concepts [31,36]. Without specific regulations that mandate the use of CE as well as raising awareness and knowledge through proper training, construction mega-projects will encounter significant challenges while adopting circularity.

The absence of incentive policy is ranked third in this study. It has been highlighted in previous works in different developed and developing countries such as the UK [28], France [32], Australia [33], and Nigeria [36]. Previous works considered the incentives to be both financial and non-financial, such as tax exemptions. These incentives are established to encourage key stakeholders to adopt more innovative circular practices and invest in the transition towards a circular economy.

Stakeholder awareness is ranked as another significant barrier to CE adoption. This finding resonates with that of studies conducted in developed countries such as the UK [28], US [31], France [32], and Australia [33]. Similar barriers have been identified in studies conducted in developing countries such as Kazakhstan [35] and Nigeria [36]. However, awareness was not always ranked as one of the most critical barriers, as shown in some other studies such as [29,30]. The barriers identified in those papers focus on tangible challenges that are related to design, regulation, and the market. This variation in ranking highlights a divergence in the understanding of circular economy and its impact across the globe.

The absence of successful examples is ranked as the fifth important barrier to CE in construction mega-projects. This barrier is not widely acknowledged as a top barrier in the literature. However, it has been acknowledged that the presence of real-world examples that adopt the circularity principle is essential to demonstrating the benefits to stakeholders [3,26]. The existence of successful examples serves as evidence of CE's feasibility and applicability in the construction mega-projects. They encourage stakeholders to adopt these principles and provide a benchmark for other projects to follow.

The absence of clear indicators and the lack of accurate data on construction waste were ranked sixth and seventh in this study. The implementation of CE in construction mega-projects is required to be measured and monitored through clear and accurate indicators, as illustrated by the authors of [3,6,35]. Effective performance indicators are essential to tracking progress towards circularity goals and validating their benefits. Furthermore, the lack of construction waste data poses a challenge for decision-makers, indicating uncertainty about adopting such a principle. This also aligns with studies conducted in France [32] and Nigeria [36], which highlight the lack of reliable data on material stocks, resulting in less effective management of waste and resources in projects. Therefore, there is a need for shared knowledge about construction material stocks to enhance the use of resources effectively.

6. Conclusions

As the construction industry consumes approximately one-third of the world's extracted natural resources, there is an urgent need to implement more sustainable practices to circulate materials and maximise their usage. While CE implementation is crucial, understanding the main barriers associated with its adoption is vital, particularly in developing countries like Saudi Arabia, where a potential growth in the construction industry has been noticed, contributing to the national GDP and the portfolio of development mega-projects across the country. Therefore, this study aimed to assess the relative importance of 24 circular economy barriers on three construction mega-projects in the context of Saudi Arabia.

The findings of the study showed minor differences in the respondents' perceptions regarding the ranking of CE barriers across the projects. However, the top seven barriers across the three construction mega-projects remained consistent with different rankings across the projects. This suggests a broad consensus on the importance of the key barriers. The most critical barriers to CE implementation in construction mega-projects in Saudi Arabia are related to legislation gaps, a lack of education and training, an absence of incentives, a lack of awareness, an absence of successful examples, and a lack of clear indicators and reliable data. These findings align with those of previous works conducted in other developed and developing countries, which emphasises the significance of these barriers limiting the full adoption of CE principles in the sector.

Based on its findings, this study suggests that government agencies in Saudi Arabia should take proactive measures to facilitate the adoption of CE by establishing laws and legislation frameworks and encouraging stakeholders in the sector. This should include the needed standards and guidelines. Additionally, incorporating circular economy principles into engineering school curricula and conducting regular trainings and workshops will contribute to professional awareness and knowledge of the best CE practices around the globe. Moreover, collaboration with experts from developed countries can facilitate the adoption of CE in the construction industry.

This study significantly contributes to the relatively sparse literature on CE adoption in construction mega-projects by employing three diverse case studies: buildings, urban development, and infrastructure in Saudi Arabia. Unlike previous studies that predominantly focus on building projects, this study covers a broader scope by examining mega-projects with different project types, thereby providing a novel comparative analysis between these case studies. This research not only deepens stakeholders' understanding of critical barriers but also provides a clearer idea of the avenues for mitigation. Furthermore, policymakers can use the results of this study to develop policies that can support construction to overcome these challenges and build a more circular construction sector. Additionally, this study has the potential to raise awareness within academic circles, promoting the integration of circular economy principles into the engineering school curricula.

While this study makes a valuable contribution to the field, there is room for further research to explore its limitations in more depth. This study considers three different construction mega-projects in Saudi Arabia. However, the findings can generalised to smaller-scale projects. Furthermore, further examinations of the success factors would ensure the easier implementation of CE in the construction sector.

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