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Factors Causing Waste in Construction of Mega-Projects: Case Studies from Saudi Arabia

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Abstract: The construction industry continues to generate vast volumes of waste, which harm the environment and negatively impact socio-economic sustainability, especially in a developing country like Saudi Arabia. Prior to investigating effective approaches for managing waste, we must identify the main drivers of construction waste. This paper develops metrics and criteria for identifying and ranking the waste cause factors (WCFs) in the construction of mega-projects in Saudi Arabia. The methodology adopted includes a thorough literature review and a survey ranking waste factors based on a five-point Likert-scale. Data collected from 239 participants across three distinct construction mega-projects were analysed using one-way analysis of variance (ANOVA) with its corresponding post hoc tests, and the identified waste factors were ranked according to their relative importance index (RII). The findings of this study indicate that the main sources of waste in Saudi Arabia involve design changes and complexity, poor project coordination, inefficient waste management systems, lack of supervision, drawing errors, low skill levels among workers and designers, and procurement mistakes. The results and discussions derived from the investigation aim to deepen the understanding of the causes of waste in large-scale construction, which could inform researchers, policymakers, and professionals, whose joint contributions should enable effective waste management strategies in large construction projects.

Keywords: waste cause factors; waste generation; construction waste; construction; building; mega-projects

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1. Introduction

Despite the significant contribution of the construction sector in urban development, which amongst other benefits, underpins the global gross domestic product (GDP), it is considered one of the primary sources of material waste and consequential environmental challenges [1–3]. The continuous growth of the construction industry foresees a substantial and sustained waste generation in the short–medium term.

Construction waste (CW), defined as unwanted materials or products generated throughout various project phases [4–6], accounts for approximately 30% of total waste volumes which, in turn, can increase material costs by more than 40% [7–9]. Furthermore, a significant amount of construction materials becomes landfill, which raises concerns, as these materials represent nearly half of total construction costs [7]. It is therefore vital to reduce waste generation and find alternatives to further promote more sustainable

construction practices that mitigate environmental challenges [1,2,10–13]. This is supported by recent studies related to recycled aggregate concrete, which highlight its potential to enhance sustainability [14,15].

The reviewed literature already highlights various classifications of key factors that contribute to construction waste. For example, Al-Rifai and Amoudi [16] categorised waste factors by their level of impact, namely, high, medium, low, and very low. Obaid et al. [17] proposed to group waste into physical (material resources) and non-physical (time and cost) groups. Other authors attribute construction waste to the project lifecycle, such as [18–21], while some others categorise it based on the factors' origins. For instance, Luangcharoenrat et al. [22] identified 28 waste factors that they subdivided into four groups considering level of significance, labelled as design and documentation, human-related aspects, construction planning and methods, and materials and procurement. Additional categories proposed in previous research include handling procedures, site conditions, and other external factors [6]. The range and variation of existing classification methods suggest a lack of agreement on how to allocate waste generating factors into appropriate groups.

Although several studies have investigated factors that contribute to construction waste, as in [16,20,23–26], many have overlooked the nature of the project, particularly large-scale projects. Furthermore, to date, no attempts have been made to examine the waste factors through project-specific case studies, limiting the practical relevance and contextualisation. Unlike previous investigations, this focuses on mega-projects, which are currently under construction in Saudi Arabia. These projects are labelled as mega based on their cost, schedule, scope, impacts, and associated risks, as suggested by [27,28].

In Saudi Arabia, the construction sector is a major contributor to its economy, as it creates around 3 million jobs and contributes about 6% to the GDP [29]. The sector continues to expand, partly to support the national strategic plan, which aims to diversify the economy and achieve sustainable prosperity. However, the construction industry accounts for 30–40% of total generated waste, leading to significant material, environmental, and financial losses [30,31]. Unfortunately, the reuse and recycling rate in this sector remains low, at just 14% [32], which highlights the need to further scrutinise the factors that contribute to waste generation. Notably, the only existing study attempting to investigate construction waste drivers in Saudi Arabia focuses on housing [33], revealing a knowledge gap also involving large-scale development.

To promote sustainable developments of large-scale projects in Saudi Arabia and similar developing countries, it is essential to identify then examine the key factors contributing to construction waste. To this end, a survey has been developed for this study to identify and rank the key factors that cause construction waste in Saudi Arabian mega-projects. The proposed methodology facilitates direct engagement with key stakeholders identified in the following three case studies: project A (building), project B (urban development), and project C (infrastructure).

Research Question: What are the factors causing waste in the construction of mega-projects in Saudi Arabia?

This paper is divided into six main sections. The first section provides an overview of construction waste production and impact, highlighting its relevance to Saudi Arabian mega-projects. The second section discusses past research on construction waste and its contributing factors. The third section outlines the research methodology for this study. The fourth and fifth sections present overall findings and discussions. Finally, the sixth section provides conclusions and recommendations for future research.

2. Literature Review

2.1. Construction Waste

Construction waste (CW) has posed a significant challenge to the sector for over a decade [34]. Yet, scholars and organisations have not come to agree on its formal definition. The European Parliament and Council [35] define CW as "waste generated by construction and demolition activities", whereas in [4–6], waste was defined as discarded or excess material produced throughout construction works. Other studies such as [6,36,37] further define CW as unwanted materials or products generated throughout the construction lifecycle, including asphalt, concrete, steel, and wood, amongst others [22,26,38]. Although the above definitions could have different interpretations, they coincide in construction waste being the result of the excessive use of resources with no added value to the project.

Most of the above studies highlight that the construction sector is a major contributor to waste [39–43], but other studies also identify the design phase as critical, as knowledge gaps and errors derive in approximately one-third of construction waste [42,44,45]. On the large scale, the CW generated throughout the entire lifecycle is estimated to represent more than 30% of total generated waste [46].

In developed countries, construction waste accounts for more than a quarter of total solid waste. In the USA and UK, it exceeds one-third of total waste, while in Germany and Australia, it represents over 19% and 38%, respectively [21,47]. In developing countries, like Malaysia, the building sector generates approximately 25,000 tons of waste per day [36]. Similarly, the Indian construction industry produces over 148 million tons of construction and demolition waste, with only 1% being recycled [48].

In the Gulf Cooperation Council countries, the construction sector of the United Arab Emirates generates more than one-third of the total waste (most of it still disposed in the landfill) despite extensive efforts to address this issue [49,50]. Similarly, in Saudi Arabia, construction waste carries approximately 35% of solids, resulting in annual losses exceeding USD 1 billion [30,31]. Furthermore, Saudi Arabia's strategic plan has driven the development of various mega-projects that aim to diversify the economy and enhance quality of life [51]. Considering the significant losses caused by construction waste, there is an urgent need to identify its root causes to gain a clearer understanding of the critical factors contributing to it. As such, this study aims to identify the causes of construction waste with a specific focus on Saudi Arabian mega-projects.

2.2. Factors Causing Waste in Construction Projects

Construction projects are essential for enhancing socio-economic prosperity and meeting the growing demand for infrastructure [52–56]. However, challenges associated with waste generation are widely recognised as major contributors to climate change and economic losses [54,57]. In this context, construction waste remains an obstacle to transforming the sector and fully embedding sustainability [58,59]; therefore, the identification of its critical causes is crucial for maximising the benefits of materials reuse [24,60,61]. A study by Elshaboury et al. [62] highlighted the trending rise of publications on construction waste management across 2020 and 2021, many of which mention the need for further investigation, particularly in developing countries.

The amount and type of construction waste are influenced by the construction method, project size, and technology [17,63]. Zighan and Abualqumbozm [64] state that the type of waste varies depending on the construction phase and stage of work. This distinction is acknowledged by Al-Rifai and Amoudi [16], who propose a classification of CW factors based on impact, namely, high, medium, low, and very low. In contrast, Obaid et al. [17] categorised CW as physical and non-physical waste, while others attribute CW causes to their origin, for example, design, human, management, and other external factors [19–21,38].

The causes of construction waste have been explored in various contexts in the literature. For example, a study by Alwi [65] investigated the root causes of waste in the Indonesian construction sector, and it revealed that a shortage of skilled labour, rework, inadequate management, and supervision are major contributors. A separate study in Indonesia by Fitriani et al. [26] identified human resource management, stakeholder collaboration in waste management, logistical and procurement challenges, and issues in the work environment as key waste generation factors. The study also emphasised that novel construction methods can effectively reduce waste and improve project performance. Furthermore, a study on Jordan by Al-Rifai and Amoudi [16] identified causes derived from lack of skilled labour, rework, poor management, and design changes. The same study identified other factors as low impact, such as infective scheduling and errors in construction drawings. Bekr [66] shortlists design changes and rework as the dominant causes of waste in the Jordanian construction sector, accounting for approximately 20% of total material wastages. Along similar lines, Al-Btoosh et al. [67] demonstrated how construction waste in Amman, the capital city of Jordan, is largely attributed to reworks caused by design changes, improper material storage, and weather-related damage. The same study notes that construction waste induces more than a 20% increase in project costs and negatively impacts overall performance.

Other studies emphasise that decisions made during the planning and design stages, such as material selection and drawing details, are key contributors to waste throughout the construction lifecycle [2,68]. As a result, several studies advocate for advanced technologies, such as building information modelling (BIM), to improve construction design management and minimisation [34,69]. Similarly, Narcis et al. [70] identified design changes, construction methods, and improper handling of materials as major factors of waste generation, and they pointed out to the need for effective waste management to reduce environmental impacts and public health issues. Similarly, Datta et al. [23] identified and ranked the key factors of CW in Bangladesh's building sector, revealing that the top contributors include material storage and quality issues, lack of training, and frequent design changes. Furthermore, external factors such as theft and vandalism were identified as significant contributors to CW in the sector. The study highlights the importance of adopting modern construction methods such as prefabrication and modular design to minimise waste throughout the construction phases.

In Egypt, Daoud et al. [71] quantified that around 40% of construction costs are wasted, and they attributed this to the following six factors: waste-efficient procurement, waste-efficient material procurement models, green materials procurement approaches, legislation, culture and behaviour, and awareness. Moreover, Ismail et al. [72] raised concerns around the disposal of CW in Egypt, noting that illegal dumping remains a major issue. Both studies suggest improvements on material procurement, promotion of best practices, education, and training as vehicles to reduce waste and integrate sustainable practices in the sector.

Moving to the Gulf Cooperation Council (GCC) countries, a study by Imran Latif et al. [73] investigated the primary causes of CW in Oman based on the opinion provided by stakeholders. According to this study, the primary causes of CW relate to design changes, poor material handling and storage, material damage during construction, and inadequate management, planning, and supervision. The lack of skilled labour and material leftovers also make significant contributions to waste.

In Saudi Arabia, Aljarallah et al. [33] focused on housing infrastructure to investigate CW. The study identified technical skill level and productivity, improper material handling and delivery, rework, and poor management and supervision as key factors contributing to construction waste. Despite the variety of findings, the scope of the study was

limited to housing infrastructure projects, leaving space to further investigate larger and distinct developments.

Despite the numerous findings reported above, Bajjou and Chafi [24] claimed that research on construction waste factors is limited despite advances in construction methods. Their study surveyed 330 professionals in Morocco to identify numerous causes of waste, which were clustered as follows: poor supervision, material management, defective planning and communication, lack of proper waste management, frequent project changes, and other external factors (often financial) affecting small and medium enterprises (SMEs) that take part in the construction chain. The authors of that investigation suggested lean and sustainability practices, such as standardisation and the 5S approach, as ways to mitigate waste. Table 1 presents the common construction waste factors in the literature.

Table 1. The common construction waste factors from the literature.

Code	Waste Causes Factor (WCF)	Reference
WCF1	Design complexity	[6,20,22,38,42,66,74]
WCF2	Errors and mistakes in design drawings	[6,20,22–24,33,38,74]
WCF3	Poor coordination and communication	[6,16,26,33,38,42,64,66,74,75]
WCF4	Document errors and issues	[6,16,20,22,38,66,76]
WCF5	Design change requests during construction	[6,20,22–24,33,38,42,74,76]
WCF6	Designers lack of experience	[6,16,23,38,42]
WCF7	Ordering errors (e.g., over-ordering)	[6,16,20,22,23,38,42,66]
WCF8	Procuring low-quality materials	[6,16,20,22,38,66]
WCF9	Damages due to improper transportation	[6,16,20,22,23,33,38,42,74]
WCF10	Insufficient handling of materials	[6,16,20,22,23,26,33,38,42,66]
WCF11	Material damages due to poor storage methods	[16,20,22,33,38,74]
WCF12	Damages in materials	[6,16,22,33,38]
WCF13	Reworks	[6,16,22,33,38,64,66,76]
WCF14	Mistakes due to lack of skills of workers	[6,16,20,22,24,26,33,38,66,76]
WCF15	Lack of supervision	[6,16,20,26,33,38,76]
WCF16	Leftover materials on site	[6,33,38]
WCF17	Inappropriate construction and erection methods	[6,20,22,38]
WCF18	Inaccuracy of planning and scheduling	[6,16,22,24,38,42,64,74,76]
WCF19	Weakness in waste management system	[6,16,20,22,42,66]
WCF20	Accidents in the construction sites	[6,24,33,42,74,76]
WCF21	Weather	[6,20,22,24,33,42]

The limited scope of prior studies, which often focus on small-scale projects or specific project types, highlights the clear gap in the literature. To help mitigate knowledge gaps, the present study examines three larger and distinct construction projects, as discussed in the following sections.

3. Methodology

3.1. Research Design

The identification of construction waste factors in mega-projects remains underexplored, particularly in developing countries such as Saudi Arabia. Case studies examining

these critical factors in distinct projects are yet to be fully investigated. To achieve this, a review of research to date is conducted to identify and rank key waste factors. The categorisation and ranking were based on the five-point Likert scale questionnaire designed to assess the waste causes and factors in mega-projects in Saudi Arabia, with the experts in the areas to capture different perspectives within the study's context [77]. Figure 1 demonstrates the methodology of the study.

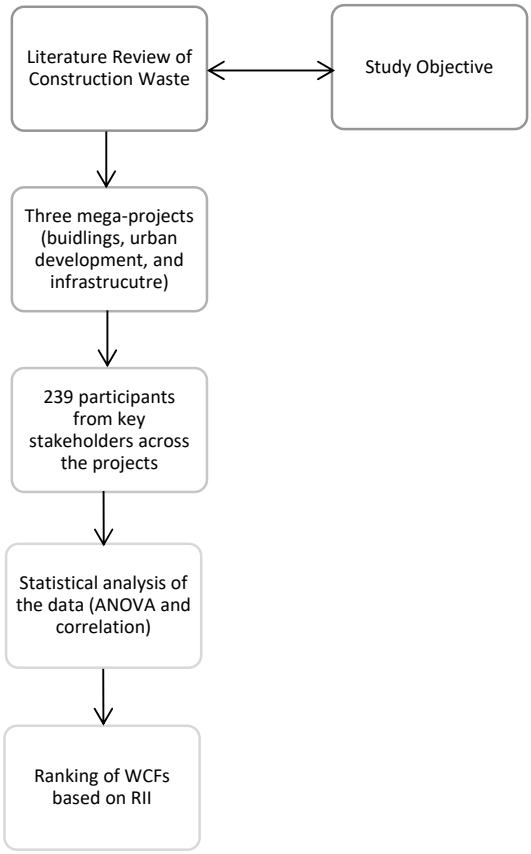

Figure 1. Overview of the research methodology.

3.2. Data Collection

The initial version of the survey was peer-reviewed by three academics and sixteen industry practitioners in the field. This review process helped enhance clarity and eliminate ambiguity. The process facilitated the consolidation of overlapping waste cause factors by combining similar ones and ensuring distinct categorisation. As a result, 21 main construction waste factors were shortlisted for the final version of the questionnaire.

To help with contextualisation, the survey begins with an introduction to the main concepts of construction waste and circular economy and links with the CE barriers discussed in a previous study [10]. The identified waste factors were initially assessed by the participants using 5-point Likert-Scale, where 5 indicates 'strongly agree' (high degree of severity) and 1 indicates 'strongly disagree'. This scale is chosen to simplify the analysis of the survey through close-ended questions. Past this point, data were analysed with the Statistical Package for Social Science (SPSS) (version 29), and the results were edited in MS Excel (version 16.81).

Moreover, parametric tests, including one-way ANOVA with its post hoc analysis and Pearson's correlation, were used to determine the significance of waste factors and investigate their interrelationship [78]. Construction waste factors were then ranked based on their Relative Importance Index (RII) following Holt [79], who discussed the benefit of

using RII in construction management particularly for providing a structured ranking of variables. The formula to calculate the RII is presented in the following Equation (1):

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

where:

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

Quantifying construction waste factors using RII provides a clear comparative measure, enabling a direct comparison of WCFs across the three construction mega-projects.

3.3. Sampling Method

A case study is an approach that involves an empirical investigation of a certain issue with its real-life context [80]. While case studies are key for investigating complex phenomena, they present challenges such as generalisability and potential bias in case selection [80]. Instead, multiple and varied case studies incorporate diverse perspectives; therefore, the alternative is best to enhance generalisability and mitigate potential bias.

This investigation involved three distinct mega-projects (case studies), selected for their significant complexity, scale, and investment. Project A refers to a large-scale commercial and residential development with a budget exceeding USD 6 billion. Project B is an urban development with a budget of more than USD 5 billion, and Project C relates to infrastructure creation with a budget of USD 3 billion. All three projects share a high level of complexity, large scale, and importance in supporting national and community growth.

The participants are professionals who are involved in both site work and office roles, ranging from directors to engineers. The sample was selected to offer broader perspectives on the factors influencing waste generation in the construction of mega-projects. The participants were selected according to their accessibility through a convenience sampling approach. Similarly, the three selected projects are categorised as mega-projects based on the criteria that were outlined by Ashkanani and Franzoi [27] and Flyvbjerg [28]. The projects are characterised by extended schedules, high complexity, considerable risks, and substantial impacts on society.

The Yamane [81] formula is used to estimate the sample size, as shown below:

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

The Yamane [81] formula is applied, taking into consideration the population size of 567 and a 95% confidence level, yielding a minimum required sample size of 235.

An invitation email, accompanied by a survey link via Google Forms, was sent to the targeted participants across the three mega-projects. To attain the minimum sample size, the invitation was sent to 345 professionals. A total of 247 responses were received; however, eight were excluded, as the respondents' roles were not directly involved in construction activities. Consequently, there were 239 final responses, representing a response rate of 69.28%, which exceeds the response rates reported in similar studies such as [82,83].

3.4. Reliability Analysis

The reliability of the data followed Cronbach's alpha coefficient (α), which ranges from 0 to 1. A higher Cronbach's alpha value indicates stronger internal consistency, subject to a threshold of 0.7 or higher to be considered acceptable [78,84].

The reliability around identified causes of construction waste was tested in two stages, namely a pilot study and a main study. The pilot study involved participants from across the three mega-projects, yielding a Cronbach's alpha value of 0.928, which indicates an excellent internal consistency. This step was essential to ensure the reliability of the questionnaire in its initial phase. The main study was graded with a Cronbach's Alpha value of 0.929, which demonstrates excellent reliability and internal consistency of the data.

3.5. Data Normality

Testing the normality of data is essential for statistical analysis. There exist various methods to assess normality, including visual examination through histograms, Q-Q plots, and other statistical parameters like skewness and kurtosis [85].

The present analysis revealed a slight skew in the histogram; however, it did not show significant deviation from normality, as shown in Figure 2. Furthermore, the Q-Q plot confirmed the normality, as the data points closely followed a diagonal line, despite minor deviations at the tail and head, as shown in Figure 3.

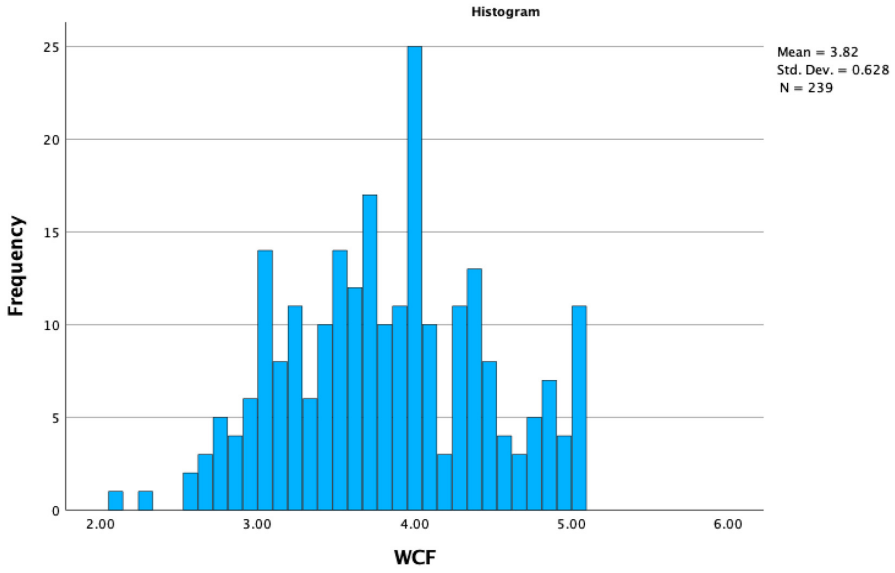

Figure 2. Histogram of waste cause factors.

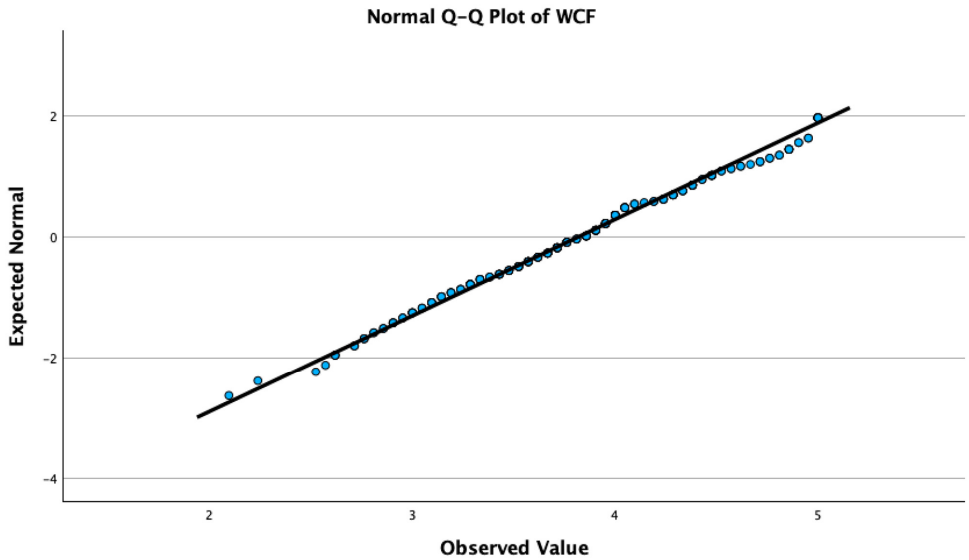

Figure 3. Q-Q plots of waste cause factors, indicating approximate normal distribution.

The estimated skewness and kurtosis values were −0.27 and −0.453, respectively, suggesting no substantial deviation from normality. Consequently, subsequent analyses of these data will assume approximate normality.

The following sections present results obtained through ANOVA tests and separate tests. These results are then used to establish categories and importance of the various identified causes that drive construction waste.

4. Findings

4.1. Demographic Profile

Those who responded to the questionnaire were involved in one of the target projects as follows: project A (87 participants), project B (81 participants), and project C (71 participants). They hold various roles, including project directors, design engineers, site engineers, and MEP specialists. Table 2 shows the qualification and level of experience breakdown of the group.

Table 2. Demographic profile of participants.

Project	Project A	87
	Project B	81
	Project C	71
Position	Design Engineer	31
	HSE Engineer	8
	MEP Engineer	19
	Procurement Manager	7
	Project Director	5
	Project Manager	65
	Quality Engineer	29
	Quantity Surveyor	17
	Site Engineer	58
Experience	Less than 5 years	65
	6 to 10 years	59
	11 to 15 years	49
	more than 15 years	66
Education	Bachelor's degree	186
	Master's degree	53

4.2. Descriptive Analysis

Table 3 presents a descriptive analysis of the waste cause factors (WCF's) in the target construction mega-projects. These factors form the sequence WCF1 to WCF21 and are compared against their level of importance as per the scale SA "Strongly Agree", A "Agree", M "Moderate", D "Disagree", and SD "Strongly Disagree". The mean and standard deviation of each waste cause factor are included, and the reader is referred to Table 1 for their description.

Table 3. Descriptive analysis of the waste cause factor data in the three construction mega-projects.

Code	SD	D	M	A	SA	Mean	Standard Deviation
WCF1	1	7	47	102	82	4.08	0.832
WCF2	1	11	48	96	83	4.04	0.878
WCF3	0	12	41	95	91	4.11	0.863
WCF4	2	14	65	93	65	3.86	0.915
WCF5	2	6	37	86	108	4.22	0.858
WCF6	1	15	52	99	72	3.95	0.899
WCF7	6	17	51	76	89	3.94	1.048
WCF8	13	28	47	79	72	3.71	1.173
WCF9	7	23	81	75	53	3.6	1.027
WCF10	6	27	65	87	54	3.65	1.029
WCF11	12	20	68	76	63	3.66	1.107
WCF12	8	34	64	74	59	3.59	1.107
WCF13	2	13	59	101	64	3.89	0.893
WCF14	1	13	55	92	78	3.97	0.902
WCF15	2	13	38	101	85	4.06	0.898
WCF16	1	26	78	82	52	3.66	0.952
WCF17	3	18	68	99	51	3.74	0.921
WCF18	4	20	62	79	74	3.83	1.015
WCF19	3	8	43	94	91	4.1	0.895
WCF20	14	38	78	70	39	3.34	1.107
WCF21	15	46	75	70	33	3.25	1.109

According to these results, WCF5 "Design changes requests during construction", WCF3 "Poor coordination and communication", and WCF19 "Weakness in waste management system" received the highest mean scores of 4.22, 4.11, and 4.1, respectively. In contrast, WCF21 "Weather" received the lowest mean of 3.25, indicating a moderate impact level.

The variability of opinions with respect to a code is reflected in the standard deviation (SD). The highest SD value of 1.173 was recorded for WCF8 "Procuring low-quality materials", suggesting some spread of opinions. In contrast, the lowest SD of 0.832 was given to WCF1 "Design complexity", indicating consistency in the collected responses.

4.3. ANOVA

The results obtained with ANOVA, shown in Table 4, indicate significant differences of perception for 15 waste cause factors (Sig. < 0.05), suggesting that these factors are driven by the nature and type of the project. In contrast, six factors did not show statistically significant differences (Sig. > 0.05), implying that these factors are perceived consistently across the three mega-projects.

Post hoc tests are conducted for those WCFs perceived different across the mega-projects. Tukey's honestly significant difference (HSD) test is used for WCFs with equal variance, and the Games–Howell test is applied to those with unequal variance. In other words, based on Levene's test results, Tukey's HSD is conducted when Levene Sig. > 0.05 and Games–Howell for Levene Sig. < 0.05.

Table 4. ANOVA test results of waste cause factors in the three construction mega-projects.

Code		Sum of Squares	df	Mean Square	F	Sig.
WCF1	Between Groups	3.343	2	1.672	2.446	0.089
	Within Groups	161.301	236	0.683		
	Total	164.644	238			
WCF2	Between Groups	4.094	2	2.047	2.691	0.07
	Within Groups	179.488	236	0.761		
	Total	183.582	238			
WCF3	Between Groups	8.858	2	4.429	6.21	0.002
	Within Groups	168.313	236	0.713		
	Total	177.172	238			
WCF4	Between Groups	4.491	2	2.245	2.722	0.068
	Within Groups	194.672	236	0.825		
	Total	199.163	238			
WCF5	Between Groups	5.074	2	2.537	3.519	0.031
	Within Groups	170.172	236	0.721		
	Total	175.247	238			
WCF6	Between Groups	8.899	2	4.45	5.726	0.004
	Within Groups	183.393	236	0.777		
	Total	192.293	238			
WCF7	Between Groups	13.709	2	6.854	6.537	0.002
	Within Groups	247.471	236	1.049		
	Total	261.18	238			
WCF8	Between Groups	42.932	2	21.466	17.803	<0.001
	Within Groups	284.566	236	1.206		
	Total	327.498	238			
WCF9	Between Groups	9.677	2	4.838	4.727	0.01
	Within Groups	241.562	236	1.024		
	Total	251.238	238			
WCF10	Between Groups	21.258	2	10.629	10.863	<0.001
	Within Groups	230.918	236	0.978		
	Total	252.176	238			
WCF11	Between Groups	24.466	2	12.233	10.809	<0.001
	Within Groups	267.082	236	1.132		
	Total	291.548	238			
WCF12	Between Groups	16.041	2	8.02	6.868	0.001
	Within Groups	275.591	236	1.168		
	Total	291.632	238			
WCF13	Between Groups	0.534	2	0.267	0.333	0.717
	Within Groups	189.416	236	0.803		
	Total	189.95	238			
WCF14	Between Groups	10.213	2	5.107	6.563	0.002
	Within Groups	183.636	236	0.778		
	Total	193.849	238			
WCF15	Between Groups	12.181	2	6.091	7.991	<0.001
	Within Groups	179.877	236	0.762		
	Total	192.059	238			

Table 4. *Cont.*

Code		Sum of Squares	df	Mean Square	F	Sig.
WCF16	Between Groups	11.509	2	5.755	6.656	0.002
	Within Groups	204.039	236	0.865		
	Total	215.548	238			
WCF17	Between Groups	5.347	2	2.674	3.21	0.042
	Within Groups	196.569	236	0.833		
	Total	201.916	238			
WCF18	Between Groups	14.74	2	7.37	7.544	<0.001
	Within Groups	230.565	236	0.977		
	Total	245.305	238			
WCF19	Between Groups	6.51	2	3.255	4.169	0.017
	Within Groups	184.277	236	0.781		
	Total	190.787	238			
WCF20	Between Groups	4.728	2	2.364	1.943	0.146
	Within Groups	287.138	236	1.217		
	Total	291.866	238			
WCF21	Between Groups	2.305	2	1.152	0.936	0.394
	Within Groups	290.632	236	1.231		
	Total	292.937	238			

Post Hoc Tests

The post hoc test relies on the Homogeneity of Variances to assess whether equal variance can be assumed. If the Levene's test gives Sig. > 0.05, then equal variance is assumed, and Tukey's HSD is applied. Conversely, if the Sig. < 0.05, the Games–Howell test is applied. Table 5 shows each waste cause factor with its corresponding significance level and selected test type.

Table 5. Waste cause factors with their corresponding significance and test type.

Code	Levene Sig.	Post Hoc Test
WCF3	0.858	Tukey HSD
WCF5	0.376	Tukey HSD
WCF6	0.202	Tukey HSD
WCF7	0.242	Tukey HSD
WCF8	<0.001	Games–Howell
WCF9	0.778	Tukey HSD
WCF10	0.088	Tukey HSD
WCF11	0.208	Tukey HSD
WCF12	0.374	Tukey HSD
WCF14	0.056	Tukey HSD
WCF15	0.436	Tukey HSD
WCF16	0.989	Tukey HSD
WCF17	0.044	Games–Howell
WCF18	0.007	Games–Howell
WCF19	0.08	Tukey HSD

Table 6 shows the pairwise comparison between the three mega-projects. These results reveal significant differences in most of the waste cause factors where Sig. < 0.05.

Table 6. Significant differences emerge in most of the waste cause factors where Sig. < 0.05.

		Multiple Comparisons			Exist of Significance
Code		**Project Type (I) vs. (J)**	**Mean Difference (I − J)**	**Sig.**	**Yes/No**
WCF3	Tukey HSD	A vs. B	−0.159	0.442	No
		A vs. C	0.318	0.05	Yes
		B vs. A	0.159	0.442	No
		B vs. C	0.478 *	0.002	Yes
		C vs. A	−0.318	0.05	Yes
		C vs. B	−0.478 *	0.002	Yes
WCF5	Tukey HSD	A vs. B	0.315 *	0.045	Yes
		A vs. C	0.287	0.089	No
		B vs. A	−0.315 *	0.045	Yes
		B vs. C	−0.028	0.978	No
		C vs. A	−0.287	0.089	No
		C vs. B	0.028	0.978	No
WCF6	Tukey HSD	A vs. B	−0.136	0.579	No
		A vs. C	0.338 *	0.045	Yes
		B vs. A	0.136	0.579	No
		B vs. C	0.474 *	0.003	Yes
		C vs. A	−0.338 *	0.045	Yes
		C vs. B	−0.474 *	0.003	Yes
WCF7	Tukey HSD	A vs. B	0.089	0.841	No
		A vs. C	0.560 *	0.002	Yes
		B vs. A	−0.089	0.841	No
		B vs. C	0.472 *	0.014	Yes
		C vs. A	−0.560 *	0.002	Yes
		C vs. B	−0.472 *	0.014	Yes
WCF8	Games–Howell	A vs. B	0.061	0.914	No
		A vs. C	0.955 *	<0.001	Yes
		B vs. A	−0.061	0.914	No
		B vs. C	0.894 *	<0.001	Yes
		C vs. A	−0.955 *	<0.001	Yes
		C vs. B	−0.894 *	<0.001	Yes
WCF9	Tukey HSD	A vs. B	−0.064	0.911	No
		A vs. C	0.405 *	0.034	Yes
		B vs. A	0.064	0.911	No
		B vs. C	0.470 *	0.013	Yes
		C vs. A	−0.405 *	0.034	Yes
		C vs. B	−0.470 *	0.013	Yes

Table 6. *Cont.*

		Multiple Comparisons			Exist of Significance
Code		**Project Type (I) vs. (J)**	**Mean Difference (I − J)**	**Sig.**	**Yes/No**
WCF10	Tukey HSD	A vs. B	−0.084	0.846	No
		A vs. C	0.607 *	<0.001	Yes
		B vs. A	0.084	0.846	No
		B vs. C	0.692 *	<0.001	Yes
		C vs. A	−0.607*	<0.001	Yes
		C vs. B	−0.692 *	<0.001	Yes
WCF11	Tukey HSD	A vs. B	−0.014	0.996	No
		A vs. C	0.693 *	<0.001	Yes
		B vs. A	0.014	0.996	No
		B vs. C	0.708 *	<0.001	Yes
		C vs. A	−0.693 *	<0.001	Yes
		C vs. B	−0.708 *	<0.001	Yes
WCF12	Tukey HSD	A vs. B	−0.054	0.943	No
		A vs. C	0.538 *	0.006	Yes
		B vs. A	0.054	0.943	No
		B vs. C	0.593 *	0.002	Yes
		C vs. A	−0.538 *	0.006	Yes
		C vs. B	−0.593 *	0.002	Yes
WCF14	Tukey HSD	A vs. B	0.088	0.796	No
		A vs. C	0.487 *	0.002	Yes
		B vs. A	−0.088	0.796	No
		B vs. C	0.400 *	0.016	Yes
		C vs. A	−0.487 *	0.002	Yes
		C vs. B	−0.400 *	0.016	Yes
WCF15	Tukey HSD	A vs. B	0.069	0.867	No
		A vs. C	0.523 *	<0.001	Yes
		B vs. A	−0.069	0.867	No
		B vs. C	0.455 *	0.004	Yes
		C vs. A	−0.523 *	<0.001	Yes
		C vs. B	−0.455 *	0.004	Yes
WCF16	Tukey HSD	A vs. B	0.026	0.982	No
		A vs. C	0.492 *	0.003	Yes
		B vs. A	−0.026	0.982	No
		B vs. C	0.466 *	0.006	Yes
		C vs. A	−0.492 *	0.003	Yes
		C vs. B	−0.466 *	0.006	Yes

Table 6. *Cont.*

		Multiple Comparisons			Exist of Significance
Code		**Project Type (I) vs. (J)**	**Mean Difference (I − J)**	**Sig.**	**Yes/No**
WCF17	Games–Howell	A vs. B	−0.107	0.741	No
		A vs. C	0.26	0.181	No
		B vs. A	0.107	0.741	No
		B vs. C	0.368 *	0.022	Yes
		C vs. A	−0.26	0.181	No
		C vs. B	−0.368 *	0.022	Yes
WCF18	Games–Howell	A vs. B	0.012	0.996	No
		A vs. C	0.549 *	0.004	Yes
		B vs. A	−0.012	0.996	No
		B vs. C	0.537 *	0.004	Yes
		C vs. A	−0.549 *	0.004	Yes
		C vs. B	−0.537 *	0.004	Yes
WCF19	Tukey HSD	A vs. B	0.141	0.557	No
		A vs. C	0.405 *	0.013	Yes
		B vs. A	−0.141	0.557	No
		B vs. C	0.264	0.159	No
		C vs. A	−0.405 *	0.013	Yes
		C vs. B	−0.264	0.159	No

* The mean difference is significant at the 0.05 level.

The post hoc analysis shows no significant differences of some WCFs across projects. For example, the statistical difference of WCF3 "Poor coordination and communication" is low when comparing project A and project B, noting that its significance exceeds the 0.05 threshold. This suggests that both projects are impacted by this factor at similar rates. On the other hand, WCF6 "Designers lack of experience" shows significant differences between project C and the pair of projects A and B. The results obtained indicate that project A and B have higher mean scores than project C, i.e., A and B face greater challenges due to "Designers lack of experience".

The Relative Importance Index (RII) of the WCFs is presented in Section 4.5 to illustrate the ranking of each WCF across the three mega-projects.

4.4. Correlation Analysis

To analyse the existence of a relationship and its strength between waste cause factors, Pearson correlation is used. Tables 7 and 8 show the results of the correlation test, which indicate positive relationships among the factors. The Pearson correlation values range from 0.042 to 0.789, highlighting different degrees of linear association between different waste cause factors.

The strongest correlation found in these results is 0.789 corresponding to WCF12 "Damages in materials" and WCF11 "Material damages due to poor storage method". Its significance stands as a 0.01 level (2-tailed), indicating a strong positive relationship with high statistical significance. This result illustrates the importance of quality control

in checking materials upon arrival at the site and ensuring proper storage in accordance with specifications.

The second and third strongest relationships are between WCF11 "Material damages due to poor storage method" and WCF10 "Insufficient handling of materials", as well as WCF11 "Material damages due to poor storage method" and WCF9 "Damages due to improper transportation", with Pearson correlation coefficients of 0.759 and 0.731, respectively. This indicates that the improper handling of materials is closely linked to both poor storage practices and inadequate transportation methods. This means that failure to properly handle and store materials on-site leads to the deterioration of material quality, waste, and poor performance.

The next Pearson correlation coefficient in the scale is 0.713 involving WCF12 "Damages in materials" and WCF10 "Insufficient handling of materials". This outcome underscores a significant interdependency between appropriate material handling on site and material damage. Poor handling exposes materials to various environmental factors, such as moisture and high temperatures, which lead to defects and loss of initial properties.

On the other side of the spectrum, the weakest relationship observed relates to WCF21 "Weather" and WCF3 "Poor coordination and communication", with a Pearson correlation coefficient of 0.042. The result seems consistent with the practical relationship amongst these factors.

The correlation values discussed above demonstrate interdependence amongst waste cause factors. All stakeholders are encouraged to bear in mind these findings when implementing actions to minimise waste and improve efficiency and sustainability in the construction industry.

Table 7. Results of Pearson's correlation test between WCFs.

Code	WCF1	WCF2	WCF3	WCF4	WCF5	WCF6	WCF7	WCF8
WCF1	--							
WCF2	0.416 **	--						
WCF3	0.229 **	0.371 **	--					
WCF4	0.296 **	0.557 **	0.472 **	--				
WCF5	0.318 **	0.289 **	0.223 **	0.340 **	--			
WCF6	0.253 **	0.386 **	0.376 **	0.343 **	0.152 *	--		
WCF7	0.232 **	0.341 **	0.277 **	0.333 **	0.356 **	0.407 **	--	
WCF8	0.264 **	0.371 **	0.405 **	0.470 **	0.257 **	0.459 **	0.557 **	--
WCF9	0.173 **	0.358 **	0.376 **	0.413 **	0.253 **	0.386 **	0.560 **	0.663 **
WCF10	0.232 **	0.379 **	0.407 **	0.447 **	0.287 **	0.406 **	0.562 **	0.691 **
WCF11	0.165 *	0.335 **	0.439 **	0.429 **	0.217 **	0.366 **	0.570 **	0.671 **
WCF12	0.189 **	0.285 **	0.363 **	0.312 **	0.197 **	0.324 **	0.505 **	0.568 **
WCF13	0.272 **	0.279 **	0.321 **	0.258 **	0.323 **	0.254 **	0.406 **	0.289 **
WCF14	0.266 **	0.261 **	0.387 **	0.332 **	0.398 **	0.319 **	0.447 **	0.422 **
WCF15	0.157 *	0.199 **	0.262 **	0.353 **	0.254 **	0.332 **	0.424 **	0.356 **
WCF16	0.250 **	0.379 **	0.306 **	0.379 **	0.319 **	0.357 **	0.452 **	0.543 **
WCF17	0.300 **	0.304 **	0.363 **	0.425 **	0.275 **	0.369 **	0.454 **	0.524 **
WCF18	0.184 **	0.347 **	0.381 **	0.476 **	0.149 *	0.317 **	0.303 **	0.481 **
WCF19	0.205 **	0.310 **	0.400 **	0.278 **	0.191 **	0.262 **	0.235 **	0.331 **
WCF20	0.218 **	0.309 **	0.238 **	0.384 **	0.101	0.344 **	0.329 **	0.495 **
WCF21	0.084	0.106	0.042	0.155 *	0.113	0.216 **	0.240 **	0.289 **

* Correlation is significant at the 0.05 level (2-tailed). ** Correlation is significant at the 0.01 level (2-tailed).

Table 8. Results of Pearson's correlation test between WCFs (continued).

Code	WCF 9	WCF 10	WCF 11	WCF 12	WCF 13	WCF 14	WCF 15	WCF 16	WCF 17	WCF 18	WCF 19	WCF 20	WCF 21
WCF 9	--												
WCF 10	0.759 **	--											
WCF 11	0.731 **	0.759 **	--										
WCF 12	0.611 **	0.713 **	0.789 **	--									
WCF 13	0.349 **	0.414 **	0.441 **	0.523 **	--								
WCF 14	0.402 **	0.407 **	0.421 **	0.410 **	0.502 **	--							
WCF 15	0.405 **	0.451 **	0.486 **	0.436 **	0.365 **	0.556 **	--						
WCF 16	0.601 **	0.583 **	0.601 **	0.543 **	0.405 **	0.455 **	0.433 **	--					
WCF 17	0.530 **	0.556 **	0.536 **	0.477 **	0.408 **	0.472 **	0.522 **	0.556 **	--				
WCF 18	0.508 **	0.511 **	0.488 **	0.392 **	0.303 **	0.376 **	0.366 **	0.424 **	0.497 **	--			
WCF 19	0.270 **	0.319 **	0.300 **	0.324 **	0.366 **	0.445 **	0.264 **	0.344 **	0.362 **	0.471 **	--		
WCF 20	0.615 **	0.558 **	0.544 **	0.556 **	0.392 **	0.316 **	0.337 **	0.521 **	0.598 **	0.507 **	0.310 **	--	
WCF 21	0.394 **	0.382 **	0.299 **	0.381 **	0.203 **	0.145*	0.157 *	0.348 **	0.397 **	0.258 **	0.174 **	0.620 **	--

** Correlation is significant at the 0.01 level (2-tailed). * Correlation is significant at the 0.05 level (2-tailed).

4.5. Relative Importance Index (RII)

4.5.1. Ranking of Waste Causes Factors for Each Construction Mega-Projects

This ranking shows variations, which are initially attributed to the nature of each project. Among the best aligned factors, we identify WCF5 "Design change requests during construction" and WCF19 "Weakness in waste management system", which position as critical causes across the three mega-projects. This result emphasises the impact of effective management systems, rules, and protocols on waste generation. On the other hand, WCF20 "Accidents in the construction sites" and WCF21 "Weather" are consistently identified as the least important factors across the three projects, yet they play a role in waste generation.

The variation of the ranking across projects is exemplified with project B (urban development) where WCF3 "Poor coordination and communication" is placed at the top of the rank but is positioned as 6th and 5th in projects A and C, respectively. This is attributed to the chain of communication whose efficiency helps to prevent mistakes that lead to rework and waste. Similarly, WCF6 "Designers lack of experience" is ranked among the top three in project B, but it is considered less important in projects A and C, where it ranks 10th and 8th, respectively. This can also be attributed to the nature of the project, as urban development projects involve distinct and unique construction activities that often require specific expertise. Table 9 provides other ranking variations across projects A, B, and C.

Table 9. Ranking of waste cause factors across the three construction mega-projects.

	Project A		Project B		Project C	
Code	**RII**	**Rank**	**RII**	**Rank**	**RII**	**Rank**
WCF 1	0.84367816	4	0.80987654	7	0.78591549	2
WCF 2	0.83908046	5	0.80493827	9	0.77464789	3
WCF 3	0.82988506	6	0.8617284	1	0.76619718	5
WCF 4	0.7862069	12	0.79259259	11	0.72957746	10
WCF 5	0.88275862	1	0.81975309	5	0.82535211	1
WCF 6	0.8	10	0.82716049	3	0.73239437	8
WCF 7	0.82758621	8	0.80987654	7	0.71549296	11
WCF 8	0.80229885	9	0.79012346	12	0.61126761	21

Table 9. *Cont.*

	Project A		Project B		Project C	
Code	**RII**	**Rank**	**RII**	**Rank**	**RII**	**Rank**
WCF 9	0.74022989	19	0.75308642	19	0.65915493	15
WCF 10	0.76091954	16	0.77777778	14	0.63943662	16
WCF 11	0.77241379	14	0.77530864	16	0.63380282	18
WCF 12	0.74712644	18	0.75802469	17	0.63943662	16
WCF 13	0.7862069	12	0.78024691	13	0.76338028	6
WCF 14	0.82988506	6	0.81234568	6	0.73239437	8
WCF 15	0.84827586	3	0.8345679	2	0.74366197	7
WCF 16	0.76321839	15	0.75802469	17	0.66478873	14
WCF 17	0.75632184	17	0.77777778	14	0.70422535	12
WCF 18	0.8	10	0.79753086	10	0.69014085	13
WCF 19	0.85287356	2	0.82469136	4	0.77183099	4
WCF 20	0.68735632	20	0.68641975	20	0.62535211	19
WCF 21	0.67356322	21	0.64691358	21	0.62535211	19

The ranking of WCFs across mega-projects reveals consistency in a number of factors, like WCF19 "Weakness in waste management system", while others exhibit degrees of variations between projects. For example, WCF5 "Design's changes requests during construction" and WCF15 "Lack of supervision" are similarly ranked in two projects but differ in the third. These variations suggest the need for stakeholders and decision makers to consider the nature and context of each project when addressing construction waste factors and implementing measures to combat the problem.

4.5.2. Overall Ranking of WCFs in Construction Mega-Projects

Table 10 presents a rank of waste cause factors in construction mega-projects based on their relative importance. The overall ranking identifies WCF5 "Design's changes requests during construction" as the most critical, followed by WCF3 "Poor coordination and communication", WCF19 "Weakness in waste management system", and WCF1 "Design complexity". These waste factors relate to different project areas, namely, decision-making, project management, and design. This demands more proactive consideration through strategic planning, effective management, and the best use of sustainability practices for design.

WCF15 "Lack of supervision", WCF2 "Errors and mistakes in design drawings", WCF14 "Mistakes due to lack of skills of workers", WCF6 "Designers lack of experience", and WCF7 "Ordering errors" seem linked to the above ones, although they are ranked separately to illustrate their impact and contribution to construction waste. To mitigate the issues associated with this sub-group, we need stricter supervision and enhanced quality control. Furthermore, upskilling through targeted training and education for workers is essential, as well as better procurement that can help reduce ordering errors and material waste. In considering these factors, waste can be reduced, ensuring an efficient use of materials while promoting sustainability in the sector.

Figure 4 demonstrates the most and least significant factors contributing to waste generation in the construction of mega-projects.

Table 10. Ranking of waste cause factors in the construction mega-projects.

Code	Waste Causes Factor	RII	Rank
WCF 1	Design complexity	0.81506276	4
WCF 2	Errors and mistakes in design drawings	0.8083682	6
WCF 3	Poor coordination and communication	0.82175732	2
WCF 4	Document errors and issues	0.77154812	11
WCF 5	Design change requests during construction	0.84435146	1
WCF 6	Designers lack of experience	0.78912134	8
WCF 7	Ordering errors (e.g., over-ordering)	0.78828452	9
WCF 8	Procuring low-quality materials	0.74142259	14
WCF 9	Damages due to improper transportation	0.72050209	18
WCF 10	Inadequate handling of materials	0.73054393	17
WCF 11	Material damages due to poor storage method	0.73221757	15
WCF 12	Damages in materials	0.71882845	19
WCF 13	Reworks	0.77740586	10
WCF 14	Mistakes due to lack of skills of workers	0.79497908	7
WCF 15	Lack of supervision	0.8125523	5
WCF 16	Leftover materials on site	0.73221757	15
WCF 17	Inappropriate construction and erection methods	0.74811716	13
WCF 18	Inaccuracy of planning and scheduling	0.7665272	12
WCF 19	Weakness in waste management system	0.81924686	3
WCF 20	Accidents in the construction sites	0.66861925	20
WCF 21	Weather	0.65020921	21

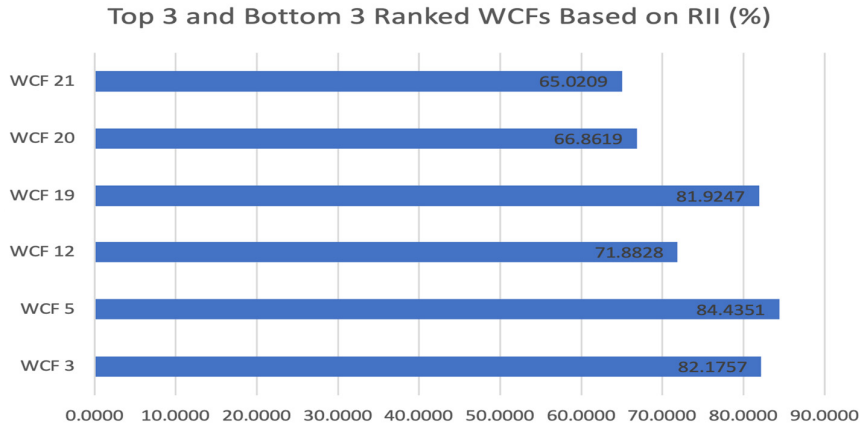

Figure 4. Top 3 and bottom 3 waste cause factors in the construction of mega-projects.

5. Discussion

Construction waste remains a key challenge in the sector, impacting both the environment and societal well-being [1–3]. Despite extensive research on the subject, notable knowledge gaps remain regarding the underlying causes of waste generation worldwide. To address this problem, this study identifies and ranks the key waste cause factors in construction mega-projects. Drawing from prior research, 21 waste cause factors (WCFs) were identified and incorporated into a survey distributed across three mega-projects under construction in Saudi Arabia (buildings, urban development, and infrastructure). The data were collected from 239 professionals representing various stakeholders to assess the relative importance of these factors in waste generation in construction mega-projects. The study of WCFs highlights variations in the opinions given by experts, which are attributed to the project nature and type.

The research findings reveal a degree of consistency in the ranking, such as WCF5 "Design's changes requests during construction" being the most critical cause of waste, particularly in projects A and C. Similarly, WCF19 "Weakness in waste management system" ranked among the top five across the three projects. In contrast, factors such as WCF15 "Lack of supervision" were highly ranked in projects A and B but were deemed less significant in project C, whereas WCF1 "Design complexity" held high importance in project C but moderate importance in projects A and B.

For low-ranked factors, WCF20 "Accidents in the construction sites" and WCF21 "Weather" show consistency across the three projects, indicating their minor contributions to construction waste generation. A cross comparison highlights an alignment (across projects) of WCF5 "Design's changes requests during construction", WCF18 "Inaccuracy of planning and scheduling", WCF20 "Accidents in the construction sites", and WCF21 "Weather", while other factors, including WCF6 "Designers lack of experience" and WCF7 "Ordering errors (e.g., over-ordering)", report slight variations. These findings emphasise the relevance of project-specific characteristics and the need for consideration when trying to minimise construction waste.

The analysis presented highlights other key factors as significant contributors to waste generation in Saudi Arabia. These include "Design's changes requests during construction", "Poor coordination and communication", "Weakness in waste management system", "Design complexity", "Lack or improper supervision", "Errors and mistakes in design drawings", "Mistakes due to lack of skills of workers", and "Designers lack of experience". Design changes and inefficient coordination lead to errors and misunderstandings, often leading to rework, which in turn generates cost overrun, schedule delays, and increased waste throughout various construction phases. It is worth noting that such findings align with previous studies, such as those by Narcis et al. [70] in Trinidad and Tobago and Gupta et al. [76] in India where design changes were ranked as the second-most critical factor contributing to waste in the building sector; while, in Jordan, the lack of waste management is considered of moderate importance [16]. Other studies, such as [16,23], discuss the importance of addressing changes in design and the lack of coordination among project parties. The study findings around weakness in waste management systems also align with past studies in developing countries where inadequate waste management is ranked among the top five causes of construction waste [24,70]. The absence of effective waste management practices results in limited recycling efforts and a lack of control overly material disposal, hence its environmental consequences.

The implementation of effective waste management systems guided by the 3Rs principles and the incorporation of appropriate transportation of surplus materials are crucial for sustainable construction in Saudi Arabia and other developing countries. It is necessary to establish governmental standards and best practice guidelines to provide a uniform approach to waste management planning, thereby minimising construction waste throughout a project's lifecycle.

Inadequate supervision and design complexity have also been confirmed as leading causes of CW. Regarding supervision issues, our findings coincide with [16] and separate studies in housing infrastructure in Saudi Arabia, where inadequate management and supervision rank among the top five according to their relative importance [33]. With respect to design complexity and errors in drawings, they ranked high in our study, as in other studies (see [14,68,73]). All these studies attribute a significant amount of construction waste to design-related issues [44]. The adoption of advanced technologies, such as building information technology (BIM), can help to reduce the errors and simplify the design process. However, a study by Datta et al. [23] in Bangladesh found that design accuracy is of minor importance to waste generation.

This and other studies undertaken in developing countries, such as [24,26,73,76], identify low workers' skills and inadequate designer experience as the primary causes of construction waste. Furthermore, research on housing infrastructure in Saudi Arabia ranks labour skill issues as a leading source of waste. In both Jordan [16] and Bangladesh [23], the lack of skilled workers is ranked among the prominent factors of CW generation, among the top three. Therefore, we need more education and training programs to improve the skills and experience of our workers.

6. Conclusions

The construction sector continues to generate significant amounts of waste, leading to the depletion of natural resources, environmental harm, and economic losses. This makes the identification of key factors that contribute to construction waste crucial, as reducing it can promote more sustainable resource use. Any improvement in developing nations such as Saudi Arabia, which is experiencing rapid growth in construction mega-projects, will support national–regional strategies and, if successful, generate impact worldwide. Therefore, this study focused on the identification and ranking of key waste generation via three case studies undertaken in Saudi Arabia.

The study findings reveal variations in the referred ranking. The eight most significant sources of construction waste relate to design changes and complexity, ineffective communication, and inadequate waste management. Errors in design drawings and specifications, lack of design expertise, and low skill levels among workers are prominent contributors. These points are consistent with previous research conducted in developing countries, notwithstanding variations of local conditions.

Our findings also suggest that government agencies in Saudi Arabia should develop more stringent measures and policies to address CW at its source. Authorities should also continue raising awareness on the importance of adopting sustainability best practices like circular economy, not only to minimise waste but also to improve project performance, as discussed in [86]. Collaboration with experts from developed nations can accelerate knowledge transfer and improve the efficiency of the local construction sector.

The objectives of this investigation were formulated past a thorough literature review on waste generation factors in construction, here tailored to mega-projects focused on building, urban development, and infrastructure in the kingdom of Saudi Arabia. Unlike studies that primarily focus on small-scale construction or only building projects or those that overlook case studies, this study adopts a broader scope by investigating the phenomena across large-scale projects adopting novel comparative analysis using statistical techniques.

The findings presented may help stakeholders such as project managers and contractors gain a deeper understanding of waste generation factors in construction mega-projects and to identify the best practices that could help mitigate them. Additionally, policymakers, such as government entities, can leverage these findings to establish appropriate legislation that supports all parties in overcoming waste generation.

This study intends to offer practical and empirical knowledge for academics and professionals and altogether underpin the mitigation of waste generation in Saudi Arabian mega-projects and developing countries with similar conditions. However, the generalisabiltiy of the results to other contexts with different social and regulatory environments is limited. Future studies could explore the potential of sustainability tools to minimise waste generation in the construction of mega-projects.

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