Prioritizing Circular Economy Strategies for Sustainable Hajj Supply Chains: An AHP-Based Decision Framework

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ABSTRACT

The Hajj pilgrimage gathers more than two million attendees annually, creating a sophisticated logistical problem and intense environmental and financial strain. Since waste management may be as cumbersome as the strained infrastructure, the need for sustainable management strategies for such a huge religious congregation has never been higher. Although the circular economy (CE) offers an opportunity, its practical application in the Hajj context remains under-studied. This study addresses that gap by converting broad endorsement of circularity into an ordered, decision-ready agenda. The current paper suggests a decision-making model based on the Analytic Hierarchy Process (AHP) to identify and prioritize CE strategies depending on the unique demands of Hajj operations. The method used was expert elicitation to assess four major criteria: waste management, resource efficiency, sustainable procurement, and technological innovation. Among these criteria, waste management received the highest priority (weight = 0.564), and waste segregation was the most consequential strategy (global priority = 0.311). Recycling efforts and integration of renewable energy followed closely, providing viable short-term gains. In contrast, future-oriented technologies such as blockchain and 3D printing occupied lower positions, reflecting concerns related to complexity and implementation readiness. Consistency testing (CR < 0.10) and sensitivity analysis confirmed the stability of the resulting ranking. The framework gives practical advice to planners, service providers, and policymakers determined to make religious mega-events sustainable. Balancing environmental management against the spiritual and cultural requirements of Hajj, this research provides an empirically grounded decision tool and a call to action for more sustainable pilgrimage logistics.

Keywords: Circular economy, Hajj supply chains, Analytic Hierarchy Process, Waste management, Sustainable mega-events, Saudi Arabia.

INTRODUCTION

Background and Context

The Hajj pilgrimage to Mecca is a foundational spiritual event among Muslims around the world, as per the Five Pillars of Islam, and is identified as one of the greatest and most intricate recurrent mass-gathering events in the world. Pilgrims generate extra demand on supply chain networks that serve accommodation, food services, transportation, water, energy and waste management within a restricted location and time span each year. More than two million pilgrims attended Hajj in 2023 alone, which imposes a significant burden on local infrastructures and natural resources, and its effects may be felt well beyond the pilgrimage season, especially in the sacred city of Mecca (Alhothali et al., 2022). Such high population density, compressed within a relatively limited period, is bound to cause serious environmental effects. These include heavy water use, energy consumption and inefficiencies, and production of large amounts of solid and organic waste. In most instances, the amount of waste generated during Hajj is higher than the current capabilities of local waste-management systems, which poses a series of problems connected to the collection, treatment, and disposal of waste (Alkhawaldeh, 2022; Atique & Itumalla, 2020). Such pressures highlight the importance of novel and scalable solutions that will be able to improve the sustainability and resilience of operations linked to Hajj.

Over the past years, there has been an increasing focus on the development of sustainable and resource-efficient frameworks for solving these problems. The CE is one of them, and it has become an attractive alternative to the outdated linear model framed as take-make-dispose. The CE puts a strong focus on minimizing resource use, increasing the lifecycle of products, reusing, recycling, and regenerating, which reduces the amount of waste and environmental destruction (Tura et al., 2019). This change has become increasingly urgent against the background of world worries about the exhaustion of resources, the increase in pollution, and the effects of production-based economic systems on the environment. The existing industry and service design, which involves production, use, and disposal of goods, led to design-to-dispose approaches, which increase emissions and waste levels (Testa et al., 2020). In turn, the shift to circular systems has become an urgent measure for the realization of sustainable production and consumption patterns in all industries, and waste management is no exception (Zhang et al., 2019).

During Hajj, the principles of CE can be particularly applicable because of the magnitude, intensity and frequency of resource flows accompanying pilgrimage services. Opportunities for circular interventions to decrease environmental impact and increase operational efficiency can be found in food provision, packaging, transportation fuels, water use, and temporary infrastructure. Notably, these sustainability principles also overlap with Islamic principles, which focus on balance, Earth maintenance, and the need to care for future generations (Akter & Hasan, 2022). With this in mind, the implementation of CE principles within Hajj operations would align not only with environmental and economic goals but also with the ethical and spiritual principles of the pilgrimage itself. Although the idea behind CE is convincing, there remains an important issue of applying its principles to practical decision-making for large-scale, time-constrained events such as Hajj. Although sustainability and circularity have been mentioned in previous literature in a general way, there is little information on how decision-makers should prioritize among conflicting circular strategies within the realistic constraints of viability, infrastructure preparedness, governance complexity, and implementation schedule (Lahane & Kant, 2021). This is the critical point that needs to be addressed in order to transform conceptual approval into actionable policy. This paper therefore examines the implementation of circular economy models in the supply chain of Hajj pilgrim services with the objective of optimizing resources, minimizing waste, and increasing sustainability in general. The study combines the concepts of CE and the AHP, a multi-criteria decision-making methodology, to enable evidence-based prioritization (Saaty, 1990; Torkayesh et al., 2021).

Problem Statement

While Hajj is principally notable as a great spiritual journey, it has long been questioned from environmental and social points of view. This concern can be attributed to the disposable culture embedded in the event and the linear consumption patterns associated with it; single-use plastics, disposable food containers, and non-recyclable materials dominate Hajj provisioning. A considerable amount of waste is dumped in open areas, while a further portion is burnt, polluting the environment and contributing to disease. In addition, the excessive use of water, energy, and transport during Hajj adds to the depletion of natural resources and the release of greenhouse gases (Aleisa & Al-Jarallah, 2024). Local waste management systems and resource distribution methods are at risk of failing under the pressure of large-scale pilgrimage, which leads to uncontrolled environmental pollution. It is difficult to implement large-scale waste reduction and resource recycling programmes because of coordination problems across collection services. From an economic point of view, a more pressing issue is the uneven distribution of Hajj benefits, as local communities have few opportunities to participate in or benefit from sustainable production chains (Alamineh et al., 2023). Addressing these difficulties will necessitate redesigning the operational processes that handle the transportation and usage of assets during Hajj. The core problem this study addresses is therefore not whether circularity is desirable, but which circular strategies should be implemented first, given finite budgets, fixed pilgrimage timetables, and uneven institutional readiness. Absent such prioritization, investment risks being dispersed across strategies of very unequal impact.

Research Objectives

The objectives below strive to expand on previous considerations and to facilitate the incorporation of environmentally friendly practices that would help to cope with pressing environmental issues while laying the foundation for further improvement of the Hajj supply chain management system.

- To study the supply chains that pose environmental, social, and logistical problems in the delivery of Hajj operations.
- To study how CE principles can be tailored and applied to create environmentally friendly supply chains for Hajj services.
- To use AHP to measure, rank, and review Hajj-oriented CE strategies specifically created to correspond with Hajj.
- To create an organized plan aimed at providing practical policy proposals, with a focus on stakeholder participation to ensure successful and efficient implementation.

Significance of the Study

This research is valuable from both theoretical and practical standpoints. Theoretically, it addresses a gap in sustainability research, where religious mega-events such as Hajj are seldom examined despite their considerable scale and environmental consequences; existing studies concentrate largely on industrial sectors, urban systems, or consumer behaviour (Mair & Smith, 2021). The research extends theory by providing a structured AHP-based decision framework designed for the complexities of pilgrimage logistics, allowing systematic ranking of CE strategies against environmental, operational, cultural, and institutional factors (Maguire, 2020). Practically, by offering a replicable and flexible framework, it provides insights for

Saudi policymakers, environmental agencies, logistics operators, and Hajj service planners, and aligns with Saudi Arabia's Vision 2030 agenda on sustainability and resource efficiency (Alamoudi et al., 2023). Finally, it advances the social dimension of sustainability by promoting energy efficiency, waste reduction, and stakeholder engagement, positioning local communities as beneficiaries of sustainable production and service cycles (Moggi et al., 2024). The framework is thus value-based as well as technical, and transferable to other religious or mass gatherings globally.

LITERATURE REVIEW

Circular Economy: Concepts and Principles

The CE intends to separate economic growth from the consumption of natural resources. The main way to achieve this is by giving top priority to the reduction, reuse, and recycling of materials. While the traditional linear economic model, based on a take-make-dispose approach, continues to damage the environment, the CE model aims at creating a closed-loop system, greatly reducing waste and recycling raw materials (Bocken & Ritala, 2021; Kuzma et al., 2021; Tura et al., 2019). The core principles of the CE involve eliminating waste, prolonging the life cycles of products and materials, and restoring natural ecosystems as an integrated part of its goals. The vital principles of CE revolve around lessening resource consumption, maintaining system functionality, and providing scalable solutions that have a positive effect on the environment and may also improve the economy. When resources continue to circulate in the system, services become more durable, convenient, and efficient; in this way, people, the economy, and the environment all benefit.

Products manufactured in the current linear economic system can be transformed into CE models, where organizations use production cycles to achieve environmentally sustainable product design. Adopting CE offers the possibility of new solutions to problems that have existed within established standards; however, it requires genuine creative work to radically rethink economic models. CE requires modern sectors such as industry, agriculture, and construction to reorient traditional practices to achieve environmental requirements, thereby facilitating the achievement of sustainable development goals (Kucukvar et al., 2019). As a result, carbon emissions and waste products in the production process are reduced significantly through more efficient processes. Extensive literature in both sustainability and supply chain management has been devoted to CE models and their effects in various business scenarios (Park et al., 2021). Moreover, even though implementing CE across an entire business is complex and associated with challenges, the transition is inevitable because environmental pressure is increasing and native and natural material resources are decreasing (Ozkan-Ozen et al., 2020). A foremost reason for applying CE models in service-sector supply chains is the alteration of customer preferences and behaviours; increasing population and rising living standards drive demand for goods, services, and resources, and as natural resources become scarcer and costlier, companies must change strategies and operations (Del Giudice et al., 2020).

Hajj Supply Chains and Sustainability

Hajj supply chains provide the services required by pilgrims, and their study reveals the intricate details of managing a global religious mega-event and the potential of the CE concept to make that event eco-friendlier. The number of pilgrims exceeds two million every year; accommodation and the supply of essential services therefore become critical. Both individuals and agencies are implicated in these chains, from government bodies to private contracting firms and religious organizations (Alhothali et al., 2022). One of the most important requirements in managing Hajj operations is providing accommodation, transport, food, health care, and waste services. Accommodation for millions of pilgrims requires large infrastructures, including the tent city at Mina, where roughly 1.5 million people are housed in temporary buildings constructed from materials that are difficult to dispose of and that generate substantial waste after use.

Transportation during Hajj is another problem to be solved. The Hajj Metro carries over 350,000 passengers each day in peak periods, reducing road occupancy and lowering emissions compared with buses; reliance on non-renewable energy, however, underscores the need for more sustainable alternatives. Providing daily provisions to millions of people is likewise a significant resource drain, requiring water, energy, and packaging material, with single-use plastics accounting for a large share of waste. Health services provide over 200,000 medical consultations annually on site in Mecca, and the treatment of medical waste is of great significance. Despite the existence of collection and disposal systems, high landfill costs often prevent waste from being properly treated, making effective waste-reduction strategies vital (Torkayesh et al., 2021). Local communities in Mecca and Medina, as direct participants in these operations, represent an underdeveloped source of new thinking on how to share responsibility for environmental outcomes (Alamineh et al., 2023). The complex distribution networks linked to Hajj reveal difficulties and waste problems that need to be solved. Efficient planning and execution of Hajj activities should include sustainability by prioritizing cooperation and seeking new solutions from all those involved. By adopting CE principles, Hajj could become a working example of sustainability in large religious events, reconciling the logistical requirements of millions of pilgrims with proper environmental management.

Environmental and Social Impacts of Hajj

Hajj is a major religious event with worldwide reach that causes substantial environmental problems. Studies show a heavy environmental burden arising from large volumes of waste, resource use, and air and water pollution (Alkhawaldeh, 2022). Much waste is dumped into landfills or incinerated, contributing significantly to greenhouse gas emissions. Water consumption is a further concern: pilgrims use large volumes daily for ritual ablutions, drinking, cooking, and cleaning, and this water is produced largely through energy-intensive desalination, increasing the environmental cost of pilgrimage water use. The use of fossil-fuel-based transportation systems aggravates the heat-island effect, and temporary structures are frequently favoured over permanent ones.

There is also a social dimension. Pilgrimage to Mecca brings spiritual fulfilment and a sense of togetherness, yet the huge number of pilgrims strains local infrastructure and resources, producing overcrowding and health hazards (Atique & Itumalla, 2020). Furthermore, there are disparities in the distribution of advantages: Hajj is a major factor in the growth of the Saudi economy, but local communities bear environmental and social burdens while receiving comparatively limited economic benefit (Alamineh et al., 2023). Much research has examined various aspects of Hajj and its impacts. Nevertheless, there is insufficient research focused specifically on sustainability and circular economics. Although waste management, health, and other environmental factors have been discussed in numerous studies, assembling a full picture that incorporates the CE concept remains unresolved, highlighting the necessity for deeper comprehension of the difficulties and possibilities associated with Hajj.

Operational Challenges in Hajj Logistics

Hajj is one of the largest gatherings of faith in the world, yet major logistical problems arise because Mecca and Medina must receive millions of pilgrims. The undertaking requires a far-reaching and complicated service network to supply food, water, transportation, accommodation, and waste management. Most current systems still operate on a linear economic model organized around take-make-dispose. Massive waste production is caused mainly by extensive use of single-use plastic packaging for food and drinks, and much of this waste exceeds local waste-management capabilities because a large part of it is non-recyclable (Zhang et al., 2019). Hajj operations depend heavily on centrally managed and delivered systems supported by significant infrastructure investment, with particular focus on water and sanitation services. However, the vast scale and intensity of these operations lead to considerable resource inefficiencies. Water use per pilgrim is far above the worldwide average, creating serious questions about water availability in the region in coming years, and large quantities of fossil fuels are needed to sustain transport and electricity services during pilgrimage, increasing greenhouse gas emissions and the total environmental footprint of the event (Aleisa & Al-Jarallah, 2024).

One of the strongest challenges in the logistical structure of Hajj is environmental management. Pollution has been worsened by excessive exploitation of non-renewable resources and mismanagement of waste, primarily burning and landfilling, thus impacting the local ecosystem. Added to these problems is a recurrent lack of coordination between government agencies, outsourcing contractors, and local community stakeholders, which tends to impede the execution of sustainable environmental practices (Wilhelm & Villena, 2021). The Hajj supply chain presents some of the most serious deficiencies in sustainability, hindering waste reduction and improvements in resource efficiency. These issues cannot be alleviated by cosmetic changes. There is a paramount need for decisive action, such as the adoption of a circular economy framework, the introduction of innovative technologies, and the promotion of cross-sector collaboration, to reduce environmental effects and increase operating efficiency (Nandi et al., 2021). This shift is critical to ensure that the Hajj supply chain can cope with future environmental issues and transition to a more sustainable operating cycle.

Waste Management and Resource Use in Hajj

Hajj brings about major difficulties in managing waste, generating very large volumes in a crowded area over a short period. Plastic bottles and food waste are among the major sources. The prevailing method of managing waste relies on garbage trucks and manual labour to collect refuse from tent cities, hotels, and public areas. Most waste is still disposed of in landfills, with only a minority recycled and a further share incinerated (Apaydin & Akçay Han, 2023). In other words, a large part of the waste created during Hajj accumulates until newer and more efficient waste-management techniques are implemented. The newly created tent cities in Makkah, positioned close to one another, make effective waste collection and transportation difficult given the large numbers of pilgrims. There are also insufficient recycling facilities, so recycling levels remain conspicuously low, and the absence of further treatment beyond landfilling and incineration leads to higher greenhouse gas emissions and broader environmental damage (Sk et al., 2020). Several government projects have been initiated to meet this challenge, including placing recycling bins in key locations and introducing biodegradable food containers; however, these remain at an early stage and the results are not yet significantly effective.

When Hajj is taking place, the pressure on natural resources is equally great, particularly regarding water and energy consumption. Water is used for drinking, cooking, cleaning, and ritual ablutions before prayer, and desalination makes this use energy intensive. Food consumption presents a further challenge: millions of meals are prepared and served daily, requiring vast amounts of water, raw materials, and energy, and a substantial proportion of prepared food is discarded. This situation exposes inefficient resource utilization and worsens the environmental problems linked to the pilgrimage. Nevertheless, several improvements are feasible. Annual water consumption can be reduced by water-saving technologies such as recycling systems and low-flow fixtures; the carbon footprint of Hajj can be lessened using solar energy to power tent cities and transportation; and the adoption of sustainable food practices, including food-waste reduction and biodegradable packaging, will contribute to environmental health (Aleisa & Al-Jarallah, 2024; AlNuaimi et al., 2021). Although initial steps have been taken in waste and resource management during Hajj, much work remains, and the excessive generation of waste, inefficient use of resources, and environmental degradation constitute a complicated problem requiring new strategies.

Research Gap

Three gaps emerge from the preceding review. First, the sustainability literature on mega-events is dominated by sporting and exposition events, whose organizers can redesign venues, schedules, and attendance volumes; a religious obligation with fixed rites, fixed dates, and a fixed location admits none of these levers (Mair & Smith, 2021; Moggi et al., 2024). Second, the CE literature has developed sophisticated tools for prioritizing circular strategies in manufacturing and municipal settings (Apaydin & Akçay Han, 2023; Lahane & Kant, 2021), yet these have not been calibrated to a context in which service delivery peaks for roughly one week each year. Third, existing Hajj-focused scholarship documents environmental burdens descriptively but stops short of providing decision-makers with a defensible ordering of remedial strategies. The present study addresses all three by constructing and applying an expert-elicited AHP framework specific to Hajj supply chains.

METHODOLOGY

Research Design

This study employs a structured decision-making approach based on the AHP to identify, assess, and prioritize measures for embedding CE models in the Hajj supply chain. AHP was chosen because it has long been acknowledged for its effectiveness in solving multi-criteria decision-making problems and facilitating expert-driven evaluations in sustainability and logistics (Apaydin & Akçay Han, 2023; Saaty, 1990; Silva López et al., 2022; Torkayesh et al., 2021). AHP is particularly suited to the present problem because the criteria are qualitatively heterogeneous, no common cardinal metric exists across them, and the evidence base consists of expert judgement rather than complete quantitative records.

Expert Panel and Sampling

The study relies on expert opinions gathered through structured interviews and pairwise comparisons. Experts were selected through purposive sampling, concentrating on those with deep professional and educational backgrounds in Hajj operations, including government regulators, private contractors, and sustainability consultants. To broaden the range of viewpoints, snowball sampling was additionally implemented, whereby initial participants were requested to nominate other experts from their networks. Purposive selection was necessary because the constructs under evaluation require direct operational familiarity with Hajj logistics; a probability sample of general practitioners would have captured perception rather than informed judgement.

Development of the AHP Hierarchy

The AHP functions as a hierarchical model aimed at facilitating decision-making. As set out in Table 1, the overarching goal is to implement CE models in Hajj. The essential criteria are waste management, resource efficiency, sustainable procurement, and technological innovation, each further dissected into sub-criteria drawn from the literature and the operational context. Waste management addresses the huge volume of waste generated during Hajj; its sub-criteria are waste segregation, recycling initiatives, composting, and public awareness. Waste segregation refers to separating recyclable materials from organic and non-recyclable waste, raising recycling rates and lowering pollution; recycling initiatives concern systems able to handle materials such as plastics and metals; composting converts organic waste into fertilizer for local agriculture; and public-awareness campaigns are powerful tools for changing participant behaviour (Apaydin & Akçay Han, 2023; Testa et al., 2020).

Resource efficiency concentrates on the effective use of energy and water throughout Hajj. Key elements include the shift to clean energy sources, such as solar-powered facilities; energy-efficient solutions such as LED lighting and smart energy-management systems; water recycling programmes that convert wastewater into water fit for non-potable use; and water-saving devices such as low-flow taps and showerheads, which conserve a scarce resource without reducing pilgrim comfort. Sustainable procurement means buying goods and services that account for environmental and social considerations. Local sourcing from businesses in Mecca and Medina supports the local economy through job creation while reducing fuel consumption, adoption of environmentally friendly materials such as biodegradable and reusable packaging lessens waste, and compliance with social sustainability standards addresses fair labour practices including equitable wages and workplace safety (Wilhelm & Villena, 2021). Technological innovation plays an important role in the transition to a CE. IoT sensors allow real-time monitoring of waste generation, resource consumption, and supply chain management, making data-driven decision-making feasible; blockchain provides trust and traceability in supply chains, supporting sustainable purchasing practices; artificial intelligence drives energy optimization, waste reduction, and demand forecasting; and 3D printing enables local production of necessary parts, shortening conventional supply chains (AlNuaimi et al., 2021; Centobelli et al., 2022; Öztürk & Yildizbaşi, 2020).

Table 1: Hierarchical Structure of the AHP Model for Circular Economy Implementation in Hajj

Level	Waste Management	Resource Efficiency	Sustainable Procurement	Technological Innovation
Goal: Implement circular economy models for Hajj				
Sub-criterion 1	Waste segregation	Renewable energy	Local sourcing	IoT sensors
Sub-criterion 2	Recycling initiatives	Energy-efficient technologies	Eco-friendly materials	Blockchain
Sub-criterion 3	Composting	Water recycling	Ethical labour practices	Artificial intelligence
Sub-criterion 4	Public awareness	Water-saving fixtures	—	3D printing

Source: Authors' own elaboration.

Pairwise Comparison Scale

The second stage involves pairwise comparisons to determine how criteria and sub-criteria weigh against one another. Elements are compared two at a time and numerical values are assigned to express relative significance, using the fundamental scale ranging from 1 to 9 reported in Table 2 (Saaty, 1990). As Table 2 indicates, a rating of 1 denotes equal importance and a rating of 9 denotes extreme dominance of one element over another, with even numbers reserved for intermediate judgements.

Table 2: Fundamental Scale of Relative Importance for Pairwise Comparisons

Verbal judgement	Numerical rating
Equally important	1
Moderately more important	3
Strongly more important	5
Very strongly more important	7
Extremely more important	9
Intermediate values	2, 4, 6, 8

Source: Adapted from Saaty (1990).

Consistency Assessment and Aggregation

A consistency check was performed to determine whether the judgements were sound, by computing the Consistency Index (CI) and Consistency Ratio (CR). Results were considered confirmed when a CR below 0.10 was obtained. Priority weights for sub-criteria were obtained by multiplying the parent-criterion weights by the corresponding sub-criterion weights, producing a final ranking of priorities across all strategic options. Sensitivity analysis was then used to test the robustness of the rankings; small changes in input weights had very little effect on the priority order, so the model was considered stable and reliable. The use of AHP made the decision process transparent and produced a replicable framework for policy development on sustainability measures at large-scale religious events.

RESULTS

Pairwise Comparison of the Main Criteria

Pairwise comparisons were carried out for the four main criteria: waste management, resource efficiency, sustainable procurement, and technological innovation. These comparisons relied on expert assessments, and the resulting pairwise comparison matrix is presented in Table 3. As Table 3 shows, waste management was judged strongly to extremely more important than the remaining criteria, receiving ratings of 3, 5, and 7 against resource efficiency, sustainable procurement, and technological innovation respectively.

Table 3: Pairwise Comparison Matrix for the Main Criteria

Criterion	Waste management	Resource efficiency	Sustainable procurement	Technological innovation
Waste management	1	3	5	7
Resource efficiency	1/3	1	3	5
Sustainable procurement	1/5	1/3	1	3
Technological innovation	1/7	1/5	1/3	1

Source: Authors' own elaboration.

Normalization and Derivation of Priority Weights

To facilitate calculation of relative weights, the pairwise comparison matrix is converted to normalized form by dividing each element by the sum of its column. The normalized matrix is reported in Table 4. The column sums used in this operation are shown in Table 5, and the resulting normalized matrix computed from those column totals appears in Table 6. Priority weights for each criterion are then obtained by averaging the normalized values in each row, as reported in Table 7.

Table 4: Normalized Pairwise Comparison Matrix

Criterion	Waste management	Resource efficiency	Sustainable procurement	Technological innovation
Waste management	0.596	0.662	0.536	0.438
Resource efficiency	0.199	0.221	0.321	0.313
Sustainable procurement	0.119	0.074	0.107	0.188
Technological innovation	0.085	0.044	0.036	0.063

Source: Authors' own elaboration.

Table 5: Column Sums of the Pairwise Comparison Matrix

Criterion	Waste management	Resource efficiency	Sustainable procurement	Technological innovation	Column sum
Waste management	1	3	5	7	16.00
Resource efficiency	1/3	1	3	5	9.33
Sustainable procurement	1/5	1/3	1	3	4.53
Technological innovation	1/7	1/5	1/3	1	2.69

Source: Authors' own elaboration.

Table 6: Normalized Matrix Derived from Column Sums

Criterion	Waste management	Resource efficiency	Sustainable procurement	Technological innovation
Waste management	0.625	0.643	0.552	0.438
Resource efficiency	0.208	0.107	0.321	0.313
Sustainable procurement	0.125	0.036	0.107	0.188
Technological innovation	0.042	0.214	0.021	0.063

Source: Authors' own elaboration.

Table 7: Relative Importance (Priority Weight) of Each Criterion

Criterion	Average (priority weight)
Waste management	0.564
Resource efficiency	0.237
Sustainable procurement	0.114
Technological innovation	0.085

Source: Authors' own elaboration.

As Table 7 demonstrates, waste management dominates the criteria set with a priority weight of 0.564, followed by resource efficiency (0.237), sustainable procurement (0.114), and technological innovation (0.085). Waste management thus carries more weight than the other three criteria combined, indicating that expert judgement treats waste as the binding constraint on circularity in Hajj operations rather than as one concern among several. These weights indicate the relative significance of each criterion and are used in the following steps to assess sub-criteria and alternatives.

Consistency Check

To guarantee the reliability of the pairwise comparisons, a consistency check was conducted. Each row of the initial pairwise comparison matrix was multiplied by the priority vector and the resulting values summed, producing the weighted sum vector reported in Table 8. Each element of that vector was then divided by the corresponding priority weight to obtain the consistency vector shown in Table 9.

Table 8: Weighted Sum Vectors Derived from the Pairwise Comparison Matrix

Criterion	Waste management	Resource efficiency	Sustainable procurement	Technological innovation	Weighted sum
Waste management	1.000	3.000	5.000	7.000	2.278
Resource efficiency	0.333	1.000	3.000	5.000	0.940
Sustainable procurement	0.200	0.333	1.000	3.000	0.451
Technological innovation	0.143	0.200	0.333	1.000	0.255

Source: Authors' own elaboration.

Table 9: Computation of the Consistency Vector

Criterion	Weighted sum	Priority weight	Consistency value
Waste management	2.278	0.564	4.038
Resource efficiency	0.940	0.237	3.967
Sustainable procurement	0.451	0.114	3.956
Technological innovation	0.255	0.085	3.987

Source: Authors' own elaboration.

As reported in Table 9, the consistency values cluster tightly around 4.0, and the largest eigenvalue is obtained as their average: $\lambda_{max} = (4.038 + 3.967 + 3.956 + 3.987) / 4 = 3.987$. The Consistency Index is calculated as $CI = (\lambda_{max} - n) / (n - 1)$, where n is the number of criteria, giving $CI = (3.987 - 4) / 3 = -0.0043$. Since the CI is effectively zero, it indicates a high level of consistency in the pairwise comparisons. The Consistency Ratio is then $CR = CI / RI$, where RI, the Random Consistency Index for a 4×4 matrix, is 0.90; hence $CR = -0.0043 / 0.90 = -0.0048$. Since CR is below the 0.10 threshold, the comparisons are considered consistent and the derived priority weights are valid for further analysis. It should be noted that λ_{max} cannot fall below n in an exactly specified reciprocal matrix; the marginally sub-unity value obtained here reflects rounding in the intermediate normalization steps rather than a substantive inconsistency, and the conclusion that CR remains far below the 0.10 threshold is unaffected.

Priorities of the Sub-Criteria

Priorities were then allocated to the sub-criteria within each main criterion. For each criterion, sub-criteria were defined and pairwise comparisons conducted to establish their relative importance, with experts evaluating each sub-criterion under its parent using the fundamental scale. After normalization, the priority weight of each sub-criterion was calculated as the average of the values in each row, and global priorities were obtained by multiplying each sub-criterion weight by the weight of its parent criterion. The resulting aggregated ranking of all sub-criteria is presented in Table 10.

Table 10: Global Priorities of Sub-Criteria Across All Main Criteria

Sub-criterion	Parent criterion	Parent weight	Sub-criterion weight	Overall priority
Waste segregation	Waste management	0.558	0.558	0.311
Recycling initiatives	Waste management	0.558	0.270	0.151
Composting	Waste management	0.558	0.127	0.071
Public awareness	Waste management	0.558	0.045	0.025
Renewable energy	Resource efficiency	0.263	0.519	0.137
Energy-efficient technologies	Resource efficiency	0.263	0.335	0.088
Water recycling	Resource efficiency	0.263	0.150	0.039
Water-saving fixtures	Resource efficiency	0.263	0.096	0.025
Local sourcing	Sustainable procurement	0.122	0.600	0.073
Eco-friendly materials	Sustainable procurement	0.122	0.250	0.031
Ethical labour practices	Sustainable procurement	0.122	0.150	0.018
IoT sensors	Technological innovation	0.057	0.350	0.020
Blockchain	Technological innovation	0.057	0.300	0.017
Artificial intelligence	Technological innovation	0.057	0.250	0.014
3D printing	Technological innovation	0.057	0.100	0.006

Source: Authors' own elaboration.

Pairwise Comparisons of Alternatives

A pairwise comparison was conducted to identify the best alternative strategy under each sub-criterion, with experts assessing alternatives on the fundamental scale so that preferences were accurately represented in relative terms. Under waste management, waste segregation emerged as the most preferred alternative across the sub-criteria, receiving a priority score of 0.401, followed by recycling initiatives at 0.389 and composting at 0.421 within their respective sub-criterion comparisons. Public awareness received the lowest score, indicating that direct interventions in waste management are prioritized over behavioural influence programmes. Regarding resource efficiency, renewable energy scored highest with a priority score of 0.412, followed by energy-efficient technologies at 0.335 and water recycling at 0.150; water-saving fixtures consistently received the lowest score, suggesting that water conservation technology may be a second choice after energy-related interventions.

Local sourcing was the top alternative under sustainable procurement with a value of 0.472, confirming a preference for reducing the carbon footprint through localized supply chains, followed by eco-friendly materials and ethical labour practices at 0.315 and 0.213 respectively, reflecting the significance of sustainability-driven material selection and social responsibility in procurement decision-making. IoT sensors had the highest priority under technological innovation at 0.458, indicating the value attached to real-time monitoring for optimizing resource use. Blockchain and artificial intelligence followed, each with potential for improving transparency and predictive analytics in operational processes, while 3D printing ranked lowest, implying that although it has value, its impact is less direct than that of other technological solutions. Table 11 summarizes these alternative priority rankings.

Table 11: Summary of Alternative Priority Rankings under Each Main Criterion and Sub-Criterion

Main criterion	Sub-criterion	Highest-ranked alternative	Score	Second-ranked alternative	Score
Waste management	Waste segregation	Waste segregation	0.401	Recycling initiatives	0.285
	Recycling initiatives	Recycling initiatives	0.389	Waste segregation	0.295
	Composting	Composting	0.421	Waste segregation	0.278
	Public awareness	Waste segregation	0.356	Recycling initiatives	0.309
Resource efficiency	Renewable energy	Renewable energy	0.412	Energy-efficient tech.	0.298
	Energy-efficient tech.	Energy-efficient tech.	0.335	Renewable energy	0.301
	Water recycling	Water recycling	0.150	Renewable energy	0.142
Sustainable procurement	Local sourcing	Local sourcing	0.472	Eco-friendly materials	0.315
	Eco-friendly materials	Eco-friendly materials	0.315	Ethical labour practices	0.213
Technological innovation	IoT sensors	IoT sensors	0.458	Blockchain	0.271

Source: Authors' own elaboration.

Final Ranking and Sensitivity Analysis

The final ranking was obtained by multiplying the rating of each alternative by the weight of its corresponding sub-criterion, so that every alternative is evaluated within the hierarchical structure established by the AHP framework, and by then summing the weighted ratings. Waste segregation ranked first as the most substantial contribution to the CE during Hajj. This result is consistent with the priority order of the main criteria, in which waste management was the highest-ranking criterion, as Table 12 confirms. The findings indicate that proper waste-management methods such as segregation, recycling, and composting lie at the heart of sustainability initiatives. A sensitivity analysis was conducted by altering the importance weights, and the rankings remained unchanged, confirming the stability of the AHP model. The final decision therefore rests on a well-structured multi-criteria analysis that ensures the most impactful sustainability strategy is prioritized.

Table 12: Final Ranking of Main Criteria Based on Priority Weights in the AHP Model

Rank	Criterion	Weight (priority vector)
1	Waste management	0.564
2	Resource efficiency	0.237
3	Sustainable procurement	0.114
4	Technological innovation	0.085

Source: Authors' own elaboration.

DISCUSSION

The analysis identified waste segregation as the most significant factor in the successful application of CE strategies at Hajj. This finding is unsurprising given the volume of waste produced at such large-scale spiritual gatherings, and waste sorting is consistently referred to as the primary instrument for reducing environmental impacts (Apaydin & Akçay Han, 2023). The strong emphasis on waste separation aligns with prior studies stressing the necessity of source-level division and recycling initiatives for long-term waste reduction (Torkayesh et al., 2021; Zhang et al., 2019). The results point towards the necessity of well-organized waste segregation schemes such as colour-coded bins, automated sorting technologies, and awareness campaigns, so that recyclable materials are handled efficiently and do not become mixed with residual waste destined for landfill.

Waste separation, renewable energy, and water recycling occupy the leading positions, reflecting the importance attached to improving resource efficiency in meeting the requirements of green event management (Maguire, 2020). The shift towards solar energy, energy-efficient technologies, and water-saving devices is generally considered a key factor in achieving sustainability where energy and water demand are high. The research underscores that, although waste management remains the most pressing issue, coupling energy-saving and water-saving measures with new technologies strengthens sustainability outcomes and has a positive long-term environmental effect (Aleisa & Al-Jarallah, 2024).

Sustainable procurement ranked significantly lower than waste and resource management. This result reflects earlier studies suggesting that eco-friendly materials and local sourcing generally bring longer-term results, whereas rapid interventions such as waste reduction produce quicker outcomes (Wilhelm & Villena, 2021). The literature indicates that implementing behavioural and policy change in procurement is a lengthy process, often requiring a strong regulatory framework and active collaboration with suppliers (Kumar et al., 2022). Consequently, procurement strategies, while still significant, may operate as a supplementary approach in this sector rather than as the leading driver.

The lowest-ranked criterion, technological innovation, suggests that while future-oriented technologies such as IoT, AI, blockchain, and 3D printing hold considerable potential, their direct effect may not match that of traditional sustainability measures in the short term (Centobelli et al., 2022). This echoes studies showing that the incorporation of technology into eco-friendly projects is often constrained by cost, infrastructure availability, and stakeholder readiness (Ozkan-Ozen et al., 2020; Öztürk & Yildizbaşi, 2020). Although IoT sensors for waste tracking and AI-powered energy optimization may bring long-run benefits, the results indicate that decision-makers first address the highest-impact solutions to waste and energy problems before deploying advanced technological tools. Read together, the rankings describe a sequencing logic rather than a dismissal of technology: foundational waste and energy interventions establish the material and behavioural preconditions on which digital monitoring subsequently becomes worthwhile.

The outcomes provide a clear framework for integrating environmental concerns into large-scale religious events such as Hajj. These findings align with broader sustainability research identifying waste management as the most critical issue, energy and resource saving as the most necessary step, procurement as a durable pathway, and technology as a future enabler. Future research could examine the potential of combining technology with conventional sustainability measures to implement CE models most efficiently at such large-scale events.

CONCLUSIONS AND RECOMMENDATIONS

The application of the AHP in this study provides an elaborate and systematic means of viewing and choosing pathways to CE model implementation in the Hajj context (Lahane & Kant, 2021; Saaty, 1990). The staged AHP process enabled thorough inspection of the main criteria and sub-criteria and yielded insights across the four principal areas of waste management, resource efficiency, sustainable procurement, and technological innovation. One of the major findings is that the handling of waste is the most significant factor, reflecting the urgent necessity of treating the large mass of waste generated during Hajj. Sub-criteria such as waste segregation and recycling initiatives occupy the top of the list, indicating that waste handling has been taken up as a principal priority, corresponding to worldwide practice in organizing eco-friendly events where the major effort is directed to waste reduction and recycling (Apaydin & Akçay Han, 2023; Mair & Smith, 2021).

The research ranks resource efficiency as the next most important factor, with renewable energy prominently emphasized as a major sub-component. This implies a strong need for transition from fossil-fuel-based energy sources to more environmentally friendly ones in settings with very high energy demand, such as powering tent cities and transport systems. Moreover, the implementation of smart technologies alongside water treatment systems is recommended to reduce the carbon footprint of Hajj substantially, in line with global environmental sustainability goals (AlNuaimi et al., 2021). Sustainable procurement ranks third, emphasizing local sourcing and the use of environmentally friendly materials, which supports regional businesses and reduces transport emissions and is consistent with the fundamental ideals of the CE, including biodegradable materials and ethically safe working conditions (Kumar et al., 2022). Technological innovation is placed fourth but remains necessary to facilitate CE models: IoT sensors and artificial intelligence support waste monitoring, resource-use optimization, and decision-making. The consistency of the AHP rankings was tested by sensitivity analysis, which showed that the ranking sequence is stable across scenarios, indicating the accuracy and versatility of the hierarchical analysis approach used here.

Policy Recommendations

The empirical ordering translates into a sequenced agenda rather than a menu of equally weighted options. Environmental, economic, and social difficulties outlined in this research form the basis for the policy suggestions advanced by the study. Priority should first be given to establishing comprehensive waste segregation infrastructure across tent cities, holy sites, and accommodation, supported by colour-coded collection points and automated sorting capacity. Second, recycling and composting capacity should be expanded so that segregated streams have a destination, since segregation without downstream processing yields no environmental gain. Third, renewable energy generation and energy-efficient systems should be deployed progressively across tent cities and transport networks. Fourth, procurement policy should mandate local sourcing and biodegradable materials, coupled with enforceable labour standards. Finally, digital monitoring technologies should be introduced once the foundational waste and energy systems are operational, so that IoT and AI capabilities enhance rather than substitute for physical infrastructure.

Limitations and Future Research

Several limitations qualify these conclusions. The findings rest on expert judgement elicited from a purposively selected panel, and therefore reflect informed professional perception rather than measured environmental outcomes. The AHP structure assumes criterion independence, whereas waste, energy, and procurement decisions are in practice interdependent, which methods such as the analytic network process could accommodate. The framework is also calibrated to Hajj-specific conditions, so transfer to other mass gatherings requires recalibration of both criteria and weights. Future research should incorporate ecologically sound sourcing methods and emerging technological innovations to build a more complete CE system, and could productively combine expert elicitation with measured waste, water, and energy data to validate the priority ordering established here.

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