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From waste to wealth: a study of concrete recycling in Jordan

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The construction industry in Jordan plays a pivotal role in the national economy but also generates a significant amount of concrete waste, leading to environmental and health challenges. Current waste management practices involve landfill use and unregulated disposal, demonstrating the country's infrastructural shortcomings in concrete waste handling. Despite the recognized importance of the construction sector and the challenges of concrete waste management, more comprehensive studies need to focus on the practicality and benefits of recycling concrete within a circular economy framework in Jordan. This gap hinders the development of effective strategies that could mitigate environmental impacts, promote sustainability, and leverage economic and social benefits in the construction industry. Given the accelerating urbanization, increasing environmental awareness, and the pressing need for sustainable development goals, the timing for this study is critical. It aims to catalyze a timely shift toward more sustainable waste management practices that align with global sustainability trends and national priorities. This study aims to fill the knowledge gap regarding the practicality of recycling concrete within a circular economy context in Jordan and explore the hypothesis that adopting circular economy principles can enhance resource efficiency, reduce waste, lower greenhouse gas emissions, foster economic benefits, and create job opportunities within the sector. Methodologically, this research comprises an analysis based on literature, international comparisons, and technical, economic, and ecological explorations of concrete recycling in Jordan. The literature study establishes a foundational understanding of the current waste management landscape, the anticipated benefits of concrete recycling, and the challenges to its implementation. Furthermore, a technical analysis evaluates the quality and applicability of recycled concrete. The in-depth examination of Jordan's concrete waste problem highlights the urbanization challenges, regulatory gaps, and environmental, social, and economic impacts. Barriers, solutions, and recommendations are discussed through an interdisciplinary lens. This integrated approach supports the transition toward a sustainable, environmentally responsible, and economically viable construction sector. The findings could contribute to policy-making and the advancement of industry practices, ultimately promoting sustainable development in Jordan.

KEYWORDS

concrete, concrete recycling, circularity, Jordan, sustainability

1 Introduction

The rapid acceleration of urbanization and infrastructural growth, especially in emerging economies, underscores the critical need for sustainable practices in the construction sector. This need is acutely felt in Jordan, where the burgeoning issue of concrete waste demands immediate attention. Our study embarks on an in-depth examination of concrete waste management in Jordan, aiming to bridge the significant knowledge gap surrounding the feasibility and advantages of recycling concrete in this context.

Grounded in a comprehensive, objective framework, our research first delineates the current landscape of concrete waste in Jordan, providing a solid foundation for understanding the magnitude and complexity of the issue. Subsequently, it assesses the potential environmental, social, and economic dividends that could be realized by integrating concrete recycling practices within the nation. The study critically evaluates the practicability of concrete recycling in Jordan, factoring in the nation's distinct environmental, regulatory, and socio-economic milieu.

Central to our investigation is the hypothesis that effective concrete recycling implementation could emerge as a linchpin for sustainable development in Jordan. This hypothesis suggests that recycling could significantly counter waste accumulation challenges while delivering substantial economic and environmental benefits. This study aims to contribute to the academic discourse on sustainable construction practices and offer actionable insights for policymakers, industry stakeholders, and the broader community engaged in Jordan's development trajectory.

2 Background: concrete waste in Jordan

2.1 Introduction to concrete waste challenges in Jordan

The study addresses the growing problem of concrete waste in Jordan, where inadequate regulations, lack of public awareness, and insufficient financial resources hinder information on recycling feasibility and its benefits. Objectives include analyzing Jordan's concrete waste situation, assessing the economic and environmental benefits, and evaluating recycling feasibility. The central question explores concrete recycling's role in Jordan's waste management and sustainability landscape. Concrete recycling could significantly contribute to sustainable development by managing waste accumulation and offering economic and environmental advantages.

The methodology involves a comprehensive literature review, technical analysis of recycled concrete, and evaluation of Jordan's concrete waste situation. It also includes economic and ecological assessments to compare the costs and benefits of recycled vs. new concrete and a practical viability analysis to gauge the steps needed for successful recycling implementation. The study concludes by reflecting on the circular economy concept to enrich knowledge and provide actionable recommendations for sustainable waste management in Jordan.

Concrete's unparalleled durability, affordability, and versatility have established it as a cornerstone of the construction industry, a sector experiencing robust global development with varying growth rates across different regions. This surge in construction activity is largely fueled by urbanization, economic expansion, and the ongoing demand for infrastructure renewal (Transparency Market Research, 2023). Moreover, the industry is transforming thanks to technological advancements like Building Information Modeling (BIM) and prefabrication, revolutionizing construction methodologies (Wu et al., 2021). As for the market growth in the region, the construction material sector within the Middle Eastern region has undergone substantial augmentation in the preceding years, fueled by a confluence of demographic expansion, the rapid pace of urban development, and significant governmental expenditures in infrastructural and property development projects.

2.1.1 The state of Jordan's and Middle East's concrete sector

In Jordan, the concrete sector has seen significant developments in recent years. The market for ready-mixed concrete and factory-made mortars in Jordan has been experiencing growth, with Italy being the largest supplier, accounting for 44% of total imports. Other key suppliers include the United Arab Emirates (17%) and China (14%). Notably, the largest markets for Jordanian exports of these products are Iraq, Palestine, and India, accounting for 76% of total exports (Indexbox, 2024). The Jordanian market has also shown notable trends regarding building blocks and bricks of cement, concrete, or artificial stone.

The United Arab Emirates is the largest supplier to Jordan in this category, comprising 62% of total imports, followed by Saudi Arabia (12%) and the Czech Republic (11%). On the export front, Qatar is the leading market for Jordan's exports in this category, making up 75% of total exports. The United States holds the second position, with a 15% share (Indexbox, 2024). Price-wise, in 2022, the average export price for ready-mixed concrete and factory-made mortars in Jordan was $506 per ton, while the import price for the same stood at $466 per ton. For building blocks and bricks of cement, concrete, or artificial stone, the average export price was $163 per ton, and the import price was $255 per ton (Indexbox, 2024).

In nations like the United Arab Emirates, Saudi Arabia, Qatar, and Oman, the construction industry flourishes, engendering a vigorous demand for building materials (Jomaa, 2023). There has been a notable recovery and growth following initial slowdowns due to the COVID-19 pandemic, with particular acceleration in sectors like residential and commercial construction, driven by low-interest rates and a shift toward suburban living in some regions. Additionally, infrastructure stimulus packages have been significant growth drivers in numerous countries.

The Middle East construction industry has an observable trend toward sustainable and eco-friendly materials (Sustainability Me News, 2023). Consequently, green construction, which focuses on efficiency and sustainability, is on the rise (Sustainability Me News, 2023). Materials such as cross-laminated timber (CLT), bamboo, and recycled materials are gaining popularity (GIZ, 2021). Despite this shift, concrete still dominates the market, and to provide a comprehensive understanding, it is important to introduce green concrete and discuss its properties, cost, and environmental impact.

Green concrete is an environmentally friendly version of traditional concrete, made from waste materials or those with a reduced carbon footprint (Cove.tool, 2023). It includes the use of industrial by-products like fly ash, silica fume, and slag cement, thereby reducing the need for virgin materials (Cove.tool, 2023).

TABLE 1 A comparative overview of green concrete and traditional concrete (Sivakrishna et al., 2020).

Property	Traditional concrete	Green concrete
Durability	Standard	Enhanced
Compressive strength	High	Comparable or slightly lower
Workability	Standard	Adjustable with admixtures
Initial cost	Lower	Higher
Lifecycle cost	Higher maintenance	Lower maintenance
Carbon footprint	High	Low
Energy consumption	High	Low
Waste reduction	Low	High

Furthermore, the properties of green concrete make it a viable and sustainable alternative in the construction industry (Cove.tool, 2023).

In terms of properties, green concrete often shows improved durability compared to traditional concrete due to the inclusion of supplementary cementitious materials (Sivakrishna et al., 2020), It typically offers similar or slightly lower compressive strength than conventional concrete, depending on the mix proportions, Additionally, the workability of green concrete can be adjusted using admixtures to meet specific construction needs (Sivakrishna et al., 2020). Regarding cost, the initial cost of green concrete can be higher due to the use of special materials and admixtures (Nilimaa, 2023). However, the long-term savings from reduced maintenance and increased durability can offset these initial expenses (Nilimaa, 2023). Over its lifecycle, green concrete can be more cost-effective due to its durability and reduced need for repairs (Estévez, 2006; Cementra, 2018; Reis, 2021; Thomas et al., 2022; Sheldon, 2023). The environmental impact of green concrete is significantly beneficial, It reduces the carbon footprint by utilizing industrial by-products, which decreases the demand for Portland cement—a major source of CO_2 emissions (Goggins, 2024). The production process of green concrete consumes less energy compared to traditional concrete, contributing to energy conservation (Cove.tool, 2023). By incorporating waste materials, green concrete helps in reducing landfill waste and promote recycling. As shown in Table 1, green concrete and traditional concrete differ significantly in terms of their properties, cost, and environmental impact.

2.1.2 Foreign and Jordan dynamics in construction

The construction market in Jordan, including both national and foreign companies, features a dynamic mix of local expertise and international influence (Times, 2023). Local firms like Manaseer Group and Cementra have deep insights into the domestic market. Manaseer Group, established in 1999, has grown significantly, now operating in various sectors including infrastructure, energy, and building materials.

They produce a range of cement and concrete products, contributing extensively to the local construction industry (Manaseer, 2020). On the other hand, foreign companies such as LafargeHolcim also play a significant role in Jordan. LafargeHolcim, as Jordan's largest cement and concrete producer, operates two major cement plants and several concrete plants across the country, providing substantial production capacity and contributing to major construction projects (Oxford Business Group, 2018).

The participation of foreign companies is influenced by local regulations, market openness, and economic conditions. For example, Jordan has policies that encourage a minimum participation of local firms in construction projects to foster domestic business growth and facilitate the adoption of international best practices (Oxford Business Group, 2018). Jordan's construction sector is geared toward addressing not only large-scale infrastructure projects but also housing needs and technological advancements, despite facing challenges such as resource limitations. These efforts are part of a broader trend in the Middle East, where countries are investing heavily in innovative city projects and infrastructure (Oxford Business Group, 2018).

2.1.3 Environmental and social impacts of concrete waste

In terms of waste management, Jordan, like many of its neighbors, is grappling with the need for improved practices and infrastructure to handle construction waste sustainably. Concrete waste from construction and demolition activities has become a significant environmental issue. The improper disposal of concrete waste creates visual pollution and poses severe threats to the environment and human health. Therefore, effectively managing concrete waste has become a crucial global challenge for governments and stakeholders in the construction sector. As for the social risks, over the last few years, waste dump landslides have entombed residential structures and human lives (Farhat, 2018).

These waste disposal sites are primarily situated near areas facing economic difficulties, where residents depend on collecting and sorting waste to contribute to their city's recycling efforts. As a result, the vulnerable communities residing in these areas are at heightened risk of experiencing severe health consequences (Farhat, 2018). Jordan is a developing country in the Middle East that faces significant challenges in handling its waste, including concrete waste. The construction sector substantially supports the country's economy but also generates a large amount of waste, predominantly in concrete and steel, attributable to substandard quality control, high redoing work, and a lack of skilled labor (Al-rifai and Amoudi, 2016).

In Jordan, construction activities are responsible for producing 30 million tons of waste, which ends up in landfill sites. Additionally, the construction industry is a significant consumer of resources, representing 40% of the country's energy usage and 12% of its freshwater consumption while contributing to 40% of the solid waste generated annually (Alawneh et al., 2019).

2.1.4 Legislative and policy framework for waste management in Jordan

Effective concrete waste management is crucial for Jordan's sustainable development and environmental protection. However, Jordan's current concrete waste management system needs to be improved. Most waste is disposed of in landfills, open dumping sites, or used as backfill materials in construction sites (Abu Hajar et al., 2021). Furthermore, the disposal of concrete waste in landfills contributes to greenhouse gas emissions and climate change through several indirect mechanisms. Each of these mechanisms involves either the release of greenhouse gases, changes in land use, or both, which exacerbate climate change. Firstly, when concrete waste is disposed of in landfills, it often contains mixed materials, including organic debris.

As these organic materials decompose in an anaerobic environment (i.e., without oxygen), they emit methane—a greenhouse gas that is significantly more potent than carbon dioxide in terms of its warming potential. This gas release significantly adds to the landfill's overall emissions (EPA, 2024). Additionally, the establishment of landfills typically necessitates significant land use changes, such as the clearing of forests or other natural habitats. These areas, especially forests, are vital for carbon sequestration; they absorb and store carbon dioxide from the atmosphere. When they are cleared, not only is this carbon storage capacity lost, but the carbon stored in the vegetation is also released back into the atmosphere, further contributing to greenhouse gas concentrations (Rodrigo-Ilarri et al., 2022). In addition, transportation also plays a role. The process of transporting concrete waste to landfill sites itself generates carbon emissions.

Concrete is notably heavy and bulky, meaning that transporting it is energy-intensive and leads to substantial fuel consumption, thus increasing carbon dioxide emissions from the vehicles used in its transport. The Climate Change Connection elaborates on the emissions from transportation activities (Kooshian, 2023). Furthermore, The operational aspects of landfills also contribute to emissions. The equipment used for managing landfills, including compactors and bulldozers, generally operates on fossil fuels. The operation of this machinery releases additional CO_2 into the atmosphere, adding to the environmental impact (Manfredi et al., 2009). Lastly, the disposal of concrete waste represents a missed opportunity for recycling. Concrete can be recycled and reused in various constructions, thereby reducing the demand for new concrete production—a process that is notably carbon-intensive. By recycling concrete, we can avoid the emissions associated with producing new materials and make better use of the embodied carbon (the carbon dioxide emitted during the production of the concrete). These points are further elaborated in Table 2, which outlines the key environmental impacts of disposing of concrete waste in landfills.

In Jordan, nearly half of the Municipal Solid Waste (MSW) is allocated to Al-Ghabawi Landfill, the solitary regulated landfill near Amman's capital. The rest is haphazardly deposited across 17 unstructured dumpsites dispersed among the nation's governorates (Abu Hajar et al., 2020). These sites do not possess the necessary environmental safeguards such as protective linings, leachate collection systems, or facilities for biogas extraction (Abu Hajar et al., 2020).

Additionally, the reuse, recycling, and recovery concept must be developed more within Jordan's waste management framework. A pronounced deficit in public awareness regarding waste management and recycling practices further exacerbates this situation. The government and private organizations are taking measures to address the solid waste issue, mainly focusing on MSW.

TABLE 2 Key points of environmental impact from disposing of concrete waste in landfills (Abu Hajar et al., 2020).

Impact area	Description
Methane emissions	Decomposition of organic materials in landfills releases methane, a potent greenhouse gas.
Land use changes	Landfills require significant land, often leading to the destruction of carbon-absorbing natural habitats.
Transportation	Transporting concrete to landfills consumes fuel, emitting CO_2 in the process.
Operational emissions	The use of fossil-fuel-powered machinery in landfill operations emits CO_2.
Recycling missed	Disposing of concrete waste prevents its reuse, necessitating more production of new, carbon-intensive concrete.

However, concrete waste is largely ignored by the Jordanian government. For example, The Jordanian Ministry of Environment ratified the "Waste Management Framework Law" for 2020. According to Article 16 of this law, "An establishment generating over one thousand (1,000) tons of nonhazardous waste annually, or any quantity of hazardous waste (excluding construction and demolition waste), must devise a waste management plan" (Ministry of Environment, 2020). Given this regulation, there is a growing need for enhanced efforts to manage the increasing volumes of waste effectively in Jordan.

The lack of proper planning, regulations, and weak enforcement have also contributed to the problem (Abu-Qdais et al., 2023). For example, the Municipalities Law, Public Health Law, and Environmental Protection Law, are general and only outline the responsible agency for waste management, fees, and fines for non-compliance, While these laws provide a foundational framework for waste management, their broad nature often results in implementation challenges. The effectiveness of these regulations is contingent on the law's specifics and the violation's nature. However, due to the general nature of some regulations, there can be difficulties in enforcement and ambiguity regarding the precise fines and penalties for non-compliance. This gap highlights the pressing need for more detailed guidelines and rigorous enforcement to effectively manage construction waste in Jordan.

However recently the Jordan government ratified a set of legislations and policies. One of these policies is the national strategy for managing solid waste, which aims to streamline management practices, introduce incremental fee increases, and incorporate circular economy solutions by 2034 (Abu-Qdais et al., 2023). However, the Jordanians still face the same problem because the primary focus was Solid waste management (SWM), not concrete waste. To have a full image of the waste management issues, it should explore the impacts of concrete waste from different perspectives. From an environmental perspective, concrete waste contributes to land degradation, pollution of water resources, and soil contamination.

In addition, the improper disposal of concrete waste can release toxic chemicals and greenhouse gases (Vaverková et al., 2019), As the heavy Metals Leaching, concrete waste often contains heavy metals such as lead, chromium, and arsenic. These metals can leach into soil and groundwater, contaminating water sources and posing health risks to humans and wildlife (EPA, 1992). In addition, when concrete waste decomposes, it undergoes carbonation, where CO_2 from the atmosphere reacts with calcium hydroxide in the concrete to form calcium carbonate.

While this process can absorb some CO_2, it is not sufficient to offset the emissions produced during cement manufacturing. Research indicates that the net effect remains a positive contribution to CO_2 emissions, exacerbating climate change (EPA, 1999). From a social perspective, concrete waste significantly impacts the quality of life of local communities (Tafesse et al., 2022). This waste can cause physical health problems like respiratory and skin irritation (Poole and Basu, 2017). It can also increase crime rates as informal landfills become a criminal activity haven (Carrington, 2016). Also, occupational risks occur at every stage in the waste management process in the informal sector, from where workers handle waste in the enterprises for collection or recycling to ultimate disposal (Jerie, 2016). In addition, manual handling tasks dominate solid waste management practices, hence the higher incidents of muscular-skeleta disorders (Jerie, 2016). Other safety and health hazards associated with waste management in informal enterprises include diarrhea, viral hepatitis, and higher incidents of obstructive and restrictive disorders (Jerie, 2016).

2.1.5 Municipal solid waste and landfill challenges in Jordan

In Jordan, improper construction waste disposal, particularly concrete, poses significant environmental threats, including pollution, soil, water, and air degradation. This issue is not unique to Jordan but is also prevalent in other developed countries (Tafesse et al., 2022). Findings from previous studies have shown the impact of construction waste in Jordan. The volume of waste received at the 17 landfills in Jordan was estimated to be approximately 1,662,939 tons in 2019. The total municipal solid waste generated by the residential population reached 2.6 million tons in 2015 (Atyyat, 2020). Managing construction and demolition (C&D) waste in Jordan faces several challenges. Nearly half of the total C&D waste generated is informal dumped, significantly impacting the environment (Alkhraisha, 2023). Strategies to handle these challenges and improve waste management practices in Jordan are outlined in Table 3.

Despite the necessity of sorting for effective solid waste management, the current system in Jordan mainly focuses on collection and disposal, without an adequate sorting (Al-rifai and Amoudi, 2016). In addition, Annually, Jordan issues construction permits encompassing approximately 11.8 million square meters, leading to a significant amount of construction and demolition (C&D) waste. There are no adequate strategies or plans to effectively handle and manage this waste (GIZ, 2014). Furthermore, it is reported that Jordan generates 2.6 million tons of solid municipal waste per year, growing annually by 5%. Only 7% of the MSW is recycled or salvaged, mainly by the informal sector (Dwarkasing, 2019).

Thousands of scavengers usually collect waste fractions of marketing value directly from the MSW collection containers dispatched over the urban cities. Then, they sort the MSW delivered to the official landfill or dumpsites through a contractual framework, but most of Jordan's waste goes untreated in landfills (UNEP, 2019). CDM Smith, one of the international privately

TABLE 3 Roadmap strategies to handle construction waste in Jordan (Saidan and Drais, 2016).

Strategy	Description	Benefits
Recycling of materials	Establish facilities to recycle materials like concrete, which can be crushed and reused in new constructions.	Reduces waste, conserves resources, and decreases environmental impact.
Material recovery	Implement systems to recover materials such as steel, wood, doors, and tiles for resale or reuse.	Reduces landfill use, generates revenue, and conserves resources.
Proper waste segregation	Enforce strict segregation of waste at the source to facilitate recycling and recovery processes.	Increases the efficiency of recycling processes and reduces contamination of recyclable materials.
Educational programs	Conduct training and awareness programs for construction workers and contractors on waste management best practices.	Enhances compliance with waste management policies and promotes sustainability in the industry.
Regulatory enforcement	Implement and enforce regulations that mandate proper disposal and management of construction waste.	Ensures that waste handling follows environmental standards and reduces illegal dumping.
Advanced processing	Introduce advanced technology to process materials like wood for other uses (e.g., conversion into particle board instead of just chicken bedding).	Adds value to waste materials, creating new business opportunities.
Partnerships	Form partnerships between government, construction companies, and recycling businesses to develop a robust recycling infrastructure.	Facilitates shared responsibility, enhances resource allocation, and improves waste handling.
Incentives for recycling	Provide incentives such as tax breaks or subsidies for companies that successfully implement waste reduction and recycling measures.	Encourages businesses to adopt waste management practices that benefit the environment and economy.
Landfill management	Develop better landfill management strategies that include designated areas for construction waste, ensuring that disposal does not harm the environment.	Reduces environmental degradation and promotes organized waste handling.
Zero waste goals	Set long-term goals for achieving zero waste in construction projects through comprehensive planning and management from the project's inception.	Promotes sustainability and resource efficiency in construction projects.

owned engineering and construction is trying to change this situation by providing professional expertise to support the recycling of reusable materials and relieve the pressure on local landfill sites while saving resources and reducing greenhouse gases (Municipality Greater Amman, 2020).

The Jordanian government is limited in its measures to handle construction waste because, to this moment, recycling or separation initiatives and infrastructure have not been integrated into Jordan's public municipal solid waste management chain and systems. Furthermore, when the construction work is done, the waste material is piled up beside the road, in places that are not allowed or near the site.

However, the contractors collect the broken concrete and bury it under the foundations of new buildings, steel and wood are carefully retrieved; the steel is either processed by hand, used again, or sold to scrapyards as scrap metal and the wood is collected for fuel or ground into small pieces and sold to chicken farms as bedding. Finally, anything that can be salvaged from the building, like doors, frames, windows, roof tiles, and bathroom fixtures, is collected and sold to secondhand dealers (Saidan and Drais, 2016).

3 Jordan construction waste management analysis aspects

3.1 Economic analysis of concrete recycling

3.1.1 The economic potential of concrete recycling in Jordan and globally

In light of the ostensible apathy exhibited by the formal sector toward the concrete recycling industry, the fiscal advantages of repurposing concrete in Jordan have been delineated as a viable strategy to bolster landfill infrastructure and augment the standard of living, particularly for those operating within the informal economy. This perspective is substantiated by a publication disseminated by the United Nations Development Programme in Jordan (Dwarkasing, 2019), where formalizing the informal waste recycling and materials recovery sector has become an economic opportunity, thereby reducing greenhouse gas emissions (Dwarkasing, 2019).

Therefore, formalizing the sector and improving the recycling infrastructure in Jordan can have significant economic benefits and contribute to the country's sustainable development, but can also have negative effects in some sectors. Recycling concrete offers significant economic benefits by reducing the need for new concrete production, a costly and resource-intensive process.

Although no studies about the economic benefits of concrete recycling for Jordan, parallels could be drawn with other contexts. For instance, according to the Environmental Protection Agency (EPA), recycling and reuse actions in the US accounted for 681,000 jobs, \$37.8 billion in wages, and generated local and state tax revenues (EPA United State environmental Protection Agency, 2023). In addition to the economic advantages, using recycled materials to replace even a small portion of concrete can significantly reduce the global carbon footprint of the cement industry, a major carbon emitter worldwide.

For instance, in the European Union, initiatives like the GREEN-FRC project have focused on creating sustainable concrete solutions by incorporating recycled and waste materials, aiming for a greener future in construction (Eurupean Commission, 2022). Countries like Japan and Canada also actively invest in concrete recycling technologies to mitigate environmental impacts. Beyond immediate environmental benefits, these efforts can lead to long-term economic advantages, including reduced raw materials costs and decreased environmental remediation expenses (Shima et al., 2005; Kizuna, 2022; Minister of Industry in Canda, 2022). By lessening the reliance on new cement production, which contributes significantly to CO_2 emissions, countries can advance toward their climate change targets and promote a more sustainable construction sector globally.

3.1.2 Challenges and opportunities in the formal sector

A monumental shift toward recycling concrete in Jordan, analogous to the gains observed in the offer considerable economic benefits. Yet, this transition may encounter resistance from stakeholders in the formal sector. Their reluctance, rooted in vested interests in conventional concrete production methods, which may be more lucrative, could impede the evolution of the recycling industry and perpetuate dependency on intensive resource usage methods. Additionally, the environmental repercussions cannot be overlooked. However, a preference for immediate profit over enduring sustainability within the industry may exacerbate ecological degradation. The lack of substantial investment in recycling infrastructure or the absence of stringent regulatory frameworks could further entrench detrimental practices.

Regarding social dynamics, the informal sector is pivotal in waste recycling and material recovery. Formalizing this sector could enhance living standards and create economic opportunities. Nevertheless, if integrating these informal entities with the formal sector is ineffectual, it might exacerbate social inequalities and overlook potential avenues for inclusive growth. Furthermore, mismanagement of waste disposal by informal operators may pose environmental and health risks. However, several sources discuss the benefits of concrete recycling in general, which may be suitable for Jordan. For example, Japan faced the same problem as Jordan fifty years ago, during Japan's modernization period, waste was managed by individuals who produced it or private operators gathering it and extracting valuable materials for sale (Ministry of the Environment, 2014).

However, these operators often dispose of the remaining waste in unsanitary ways, such as dumping it on roadsides or empty spaces, resulting in hazardous waste accumulation (Ministry of the Environment, 2014). Furthermore, in the aftermath of the war, Japan had to confront the challenge of managing urban waste (Ministry of the Environment, 2014). This put municipalities in a difficult position against the expansion of waste-related problems, necessitating a revamp in waste management.

The conclusion emphasizes that recycling concrete in Jordan offers considerable economic benefits, such as enhanced landfill infrastructure, improved living standards, especially in the informal sector, and reduced CO_2 emissions, despite potential resistance from stakeholders and the need for investment in recycling infrastructure and regulatory frameworks.

3.2 Technical analysis of concrete recycling

3.2.1 Enhancing the quality of recycled concrete

Recycled concretes are produced by crushing and processing concrete waste from demolished structures, such as buildings, bridges, and roads (Silva et al., 2014). The process typically involves removing reinforcing steel and other impurities and crushing the concrete into smaller aggregate pieces (Ghorbani et al., 2019). These recycled aggregates can replace natural aggregates in new concrete mixtures, providing similar or improved properties to conventional concrete (Silva et al., 2014). This approach aligns with the principles of the circular economy, which emphasizes the reuse and recycling of materials to minimize waste and reduce environmental impact (Ghisellini, 2016). The steps involved in the concrete recycling process are depicted in Figure 1.

3.2.1.1 Technical properties of recycled concrete

Some of the critical technical properties of recycled concrete that should be considered when evaluating its suitability for use in construction projects include:

Compressive strength: recycled concrete generally exhibits similar or slightly lower compressive strength than conventional concrete, depending on the quality of the recycled aggregate and the concrete mix design. hen high-quality recycled aggregates are used, the compressive strength of the resulting concrete can be comparable to that of conventional concrete. Studies, such as those conducted by Silva et al. (2014), have demonstrated that recycled concrete can achieve compressive strength values within the acceptable range for structural applications. For instance, recycled concrete with a compressive strength of 30 MPa has been reported, which is suitable for many constructions uses (Silva et al., 2014).

Durability: recycled concrete has been found to have comparable or slightly lower durability compared to conventional concrete, depending on factors such as the quality of the recycled aggregate, the concrete mix design, and the exposure conditions (Malešev et al., 2011). However, optimizing the mix design and using appropriate supplementary cementitious materials makes it possible to produce recycled concrete with similar or improved durability compared to conventional concrete (Kou, 2012).

Workability: recycled concrete can exhibit similar workability to conventional concrete, although it may require slightly more water to achieve the same level of workability due to the higher porosity and water absorption of recycled aggregates (Pedro et al., 2014a,b). Despite this, workability, often measured by the slump test, remains essential for ensuring the concrete mixture is practical for construction use. Recycled concrete mixtures have demonstrated similar slump values (e.g., 75–100 mm) compared to conventional concrete, indicating adequate workability for various construction projects. This can be effectively managed by using appropriate mix designs and admixtures to improve the workability of the recycled concrete mixture Improving the Quality of Recycled Concrete (Pedro et al., 2014a,b) .

Several strategies can be employed to improve the quality of recycled concrete, making it more suitable for high-strength structural applications:

Use of high-quality recycled aggregates: the quality of recycled aggregates significantly impacts the properties of recycled concrete. Using high-quality recycled aggregates obtained from selective demolition processes and advanced processing techniques makes it possible to produce recycled concrete with properties comparable to conventional concrete (Silva et al., 2014). From an environmental perspective, using recycled concrete reduces the need for virgin aggregates and decreases landfill waste,

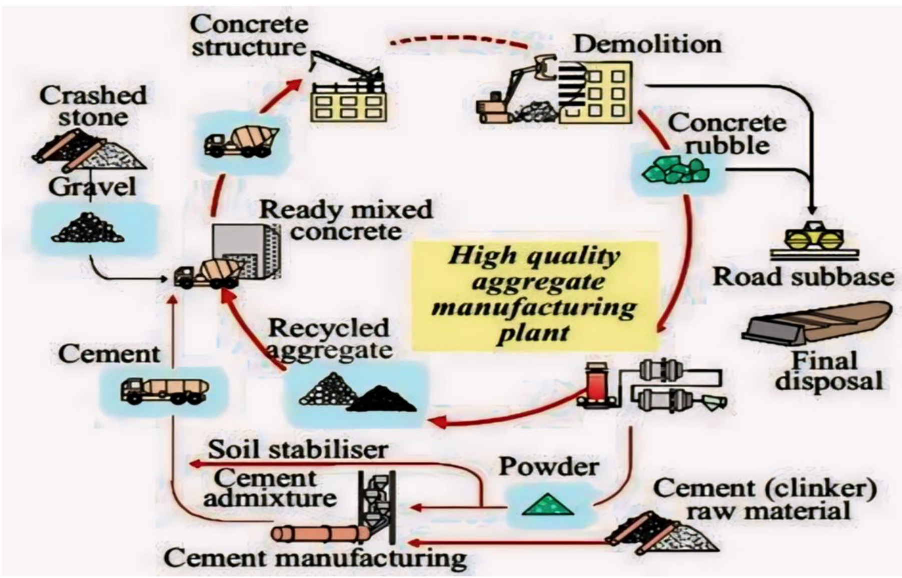

FIGURE 1
The steps of concrete recycling (Ganiron, 2015).

thus promoting sustainable construction practices. For instance, recycling one ton of concrete waste can save approximately 900 kg of CO_2 emissions, which highlights the environmental benefits of this approach (Maleševet al., 2011).

Optimization of concrete mix design: the concrete mix design plays a crucial role in determining the properties of recycled concrete. Optimizing the mix design, including the use of appropriate supplementary cementitious materials, can produce recycled concrete with similar or even improved properties compared to conventional concrete (Pacheco-Torgal and Jalali, 2010a,b).

Use of chemical and mineral admixtures: the use of chemical and mineral admixtures can significantly enhance the properties of recycled concrete. For example, the inclusion of superplasticizers, fly ash, and silica fume can improve strength, durability, and workability (Zega and Di Maio, 2011). The presence of chemical admixtures like superplasticizers specifically helps to optimize the performance of recycled concrete. The addition of silica fume, in particular, has been shown to increase the compressive strength of recycled concrete by up to 20%, while also lowering the water-cement ratio, further enhancing the concrete's overall performance (Zega and Di Maio, 2011).

Advanced treatment of recycled aggregates: techniques such as thermal, mechanical, and chemical treatments can enhance the properties of recycled aggregates. For example, thermal treatment can reduce the porosity and improve the quality of recycled aggregates, leading to better performance of the recycled concrete (Tam, 2005).

Surface coatings for recycled aggregates: applying surface coatings to recycled aggregates can mitigate their higher water absorption and porosity, enhancing the overall quality of the recycled concrete. Coatings can include materials such as silane, which improves water resistance and durability (Gómez-Soberón, 2002).

3.2.1.2 Circular economy and recycled concrete

The concept of the circular economy is particularly relevant to the recycling of concrete. The circular economy model focuses on extending the life cycle of products, minimizing waste, and making the most of resources (Ellen MacArthur Foundation, 2013). In the context of concrete, this involves the reuse of concrete waste as recycled aggregates, thus reducing the demand for natural aggregates and lowering the environmental impact of construction activities. This sustainable approach not only conserves natural resources but also reduces the carbon footprint associated with the production and transportation of new materials.

Moreover, innovations in material science are pushing the boundaries of what is possible within a circular economy for concrete. Researchers are developing new types of concrete that incorporate industrial by-products such as fly ash, slag, and silica fume, which not only enhance the performance characteristics of the concrete but also provide a sustainable outlet for these waste materials. This approach not only reduces the environmental impact associated with traditional concrete production but also fosters a symbiotic relationship between different industries, creating a more resilient and sustainable industrial ecosystem (Schneider, 2019).

In conclusion, the use of recycled concrete in Jordan is not only feasible but can also be advantageous when high-quality recycled aggregates are employed, and the concrete mix design is optimized. Quantitative data supports that recycled concrete can achieve compressive strengths of up to 30 MPa, comparable to conventional concrete, depending on the quality of the recycled aggregate and the mix design (Silva et al., 2014). Recycled concrete has shown comparable workability to conventional mixtures, with slump values ranging from 75 to 100 mm, indicating sufficient workability for various construction applications (Pedro et al., 2014a,b). Durability tests, including resistance to freeze-thaw cycles and sulfate attack, have demonstrated that recycled concrete can achieve similar or improved performance when supplementary cementitious materials are used, such as fly ash or silica fume, which enhance its durability by reducing permeability (Zega and Di Maio, 2011; Kou, 2012).

Moreover, the environmental benefits are significant, as recycling one ton of concrete waste can save approximately 900 kg of CO_2 emissions, contributing to sustainable construction practices (Maleševet al., 2011). These physical and chemical parameters highlight the potential for recycled concrete to meet or exceed the performance of conventional concrete in structural applications. Further research tailored to Jordan's specific environmental conditions will refine these findings and promote the adoption of recycled concrete for sustainable construction (Pacheco-Torgal and Jalali, 2010a,b).

3.2.2 Properties and performance of recycled concrete

The properties of recycled aggregate concrete (RAC), such as compressive strength, particle size distribution, water absorption rate, and specific gravity, significantly influence its suitability. For instance, recycled aggregate concrete typically exhibits compressive strength ranging from 20 to 35 MPa, depending on the quality of the recycled materials used (Yehia et al., 2015). Additionally, the water absorption rate of recycled aggregates, which can be as high as 3%, is higher compared to natural aggregates, affecting the concrete's overall durability and workability. These properties are influenced by the original conditions of the demolished structures and the recycling process (Kim et al., 2020). Recycled aggregate is a viable alternative to natural aggregate, offering environmental benefits and contributing to sustainable development.

However, variability in the properties of recycled aggregate, influenced by factors such as the quality of materials being collected and delivered to recycling plants, poses challenges. Ensuring the consistent production of high-quality recycled aggregate remains a complex task due to these factors (Kim et al., 2020).

Durability and long-term performance: durability is a critical factor affecting the long-term performance of RAC. Various research efforts have focused on evaluating recycled aggregate's physical and mechanical properties and its impact on concrete durability. Challenges in enhancing the durability of RAC include high porosity, absorption capacity, and the presence of contaminants. These issues can lead to a reduction in mechanical properties and affect the concrete's fresh-stage properties.

However, strategies such as achieving saturated surface dry conditions, using supplementary cementitious materials, and considering aggregate absorption during mix design can improve RAC's properties. Using materials like fly ash, silica fume, and ground-granulated blast-furnace slag has improved strength and durability by enhancing the pore structure and reducing the macro pores (Yehia et al., 2015).

Microstructural analysis: scanning Electron Microscopy (SEM) scans have been used to investigate the microstructural features of RAC, particularly focusing on the interfacial transition zone between the cement paste and the recycled aggregate. These studies reveal insights into the concrete's bond strength and potential weaknesses. For example, a porous layer was observed at the interfacial transition zone in mixes with high chloride ion permeability, contributing to higher absorption and permeability. Understanding these microstructural characteristics is crucial for improving the long-term performance of RAC (Yehia et al., 2015). As illustrated in Figure 2, the schematic diagram of interfacial transition zones (ITZs) provides a visual representation of these critical areas.

3.2.3 Regional insights and global practices

A study in Iraq, a country with similar regional characteristics to Jordan, demonstrated the feasibility of recycling concrete from construction and demolition waste; the study "Environmental Management Guidelines for Debris Recycling Sites in Iraq" by UNEP provides a framework for managing debris recycling operations in an environmentally safe and effective manner. These guidelines were developed in response to the substantial amount of rubble generated in Iraq. They emphasize debris recycling as a cost-effective and environmentally friendly option. The guidelines aim to promote a wider circular economy approach, integrating the recycling and reuse of construction and demolition waste in the sector (U. N. Environmental Program, 2020).

Furthermore, A comprehensive study in Egypt explored the application of recycled construction and demolition waste in new construction projects. The study, highlighted the technical and economic feasibility of using recycled aggregates in concrete production. The findings indicated that recycled concrete could meet local construction standards, providing a sustainable alternative to natural aggregates. The study also pointed out the challenges faced, such as the need for improved sorting and processing facilities, which are crucial for ensuring the quality of recycled materials (Attia, 2020).

Globally, the practice of recycling concrete is gaining traction. A five-year study showed that recycled concrete can perform well or even better than conventional concrete in building foundations and municipal sidewalks (GCR Staff, 2020). This finding suggests a potential for recycled concrete's use in structural applications, a trend observed in several countries. For example, the German Committee for Structural Concrete limits the proportion of recycled aggregate to 45%. However, tests in Switzerland have shown high-quality concrete can be produced with over 90% recycled aggregates.

This indicates the viability of recycled concrete in maintaining structural integrity (Souza, 2020). In the United States, the Federal Highway Administration has been promoting the use of recycled materials in road construction. A key report, "Use of Recycled Concrete Aggregate in PCCP: Literature Search," outlined how recycled concrete aggregates could be successfully used in concrete pavements.

The report highlighted significant cost savings and environmental benefits, demonstrating that recycled concrete could effectively replace a portion of virgin aggregate without compromising the structural performance of pavements (Keith and Anderson, 2009). Moreover, countries worldwide

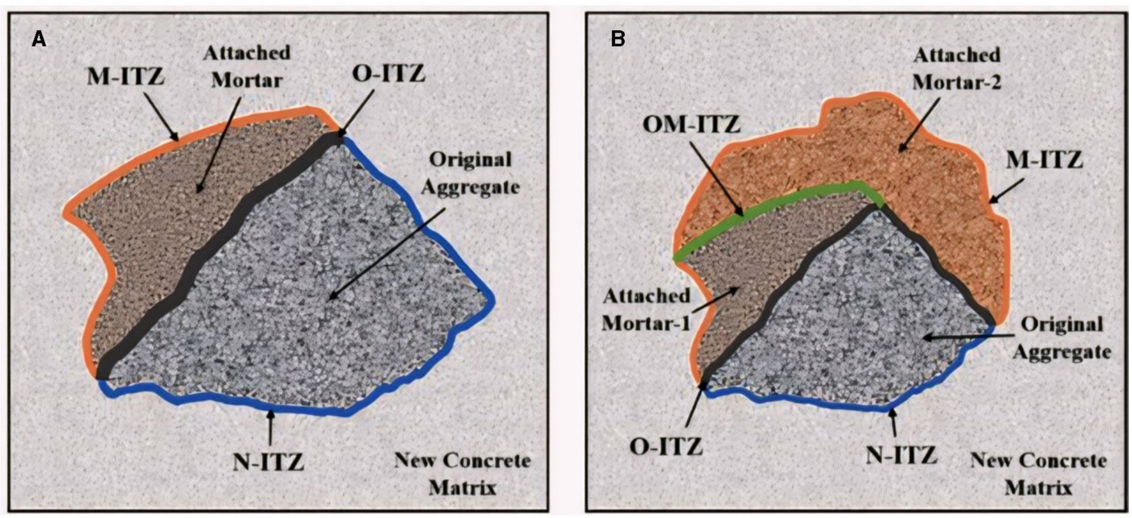

FIGURE 2
Schematic diagram of interfacial transition zones (ITZs). **(A)** M-ITZ: mortar interfacial transition zone, O-ITZ: original aggregate interfacial transition zone, N-ITZ: new concrete matrix interfacial transition zone, attached mortar. **(B)** OM-ITZ: original mortar interfacial transition zone, M-ITZ: mortar interfacial transition zone, O-ITZ: original aggregate interfacial transition zone, N-ITZ: new concrete matrix interfacial transition zone, attached mortar-1, attached mortar-2 (Liu et al., 2021).

are standardizing the use of recycled concrete in structural applications, acknowledging its sustainability benefits. The composition of recycled concrete, which typically replaces the natural aggregate in new concrete, lends it adaptability and flexibility, making it suitable for retaining walls, roads, sidewalks, and increasingly structural components (University of British Columbia Okanagan Campus, 2020).

Considering these international practices and studies, adopting recycled concrete in Jordan appears feasible and promising. The benefits include not only environmental gains by reducing the extraction of natural resources but also potential improvements in the structural quality of concrete. Jordan could look to these global examples to develop guidelines and standards for using recycled concrete in various construction applications, tailoring the approach to local conditions and requirements. In addition, the management of construction and demolition waste presents multifaceted challenges.

A study exploring this issue identified several causes for increased waste and barriers to implementing effective management strategies. A primary concern is inadequate waste management infrastructure, including physical facilities and regulations. This situation contributes to unsustainable practices, such as inefficient use of raw materials. Addressing these challenges requires a holistic approach considering infrastructure, economic conditions, and skilled labor availability (Alshdiefat et al., 2023).

The conclusion emphasizes that recycling concrete in Jordan is a viable alternative with the potential for similar or improved technical properties over conventional concrete, advocating for further research and development to adapt to local conditions and drawing parallels with global practices that showcase the successful application and environmental benefits of recycled concrete in structural uses.

3.3 Ecological analysis of concrete recycling

The estimated degradation time of concrete can vary significantly, typically spanning between 50 and 100 years. This variation is largely influenced by environmental conditions and the quality of construction materials. Another significant environmental concern at landfill sites is methane production, predominantly sourced from the decomposition of organic materials embedded in waste concrete or accumulated over time. Additionally, when waste concrete materials are disposed of in landfills, they can release hazardous chemicals and pollutants. Prominent among these are heavy metals such as lead, cadmium, and mercury, along with various chemical additives utilized during concrete production. These substances are capable of leaching into the environment, contributing to the toxic profile of landfill leachate, which poses serious health risks to both ecological systems and human populations (Rincon et al., 2024). As illustrated in Figure 3, the leachates in waste landfills contain a variety of harmful substances, underlining the urgent need for effective waste management strategies.

3.3.1 Jordan waste landfill impact

A preeminent advantage of waste reduction is the mitigation of the voluminous refuse accumulated in landfills. These waste repositories have deleterious consequences on the environment and human wellbeing. As refuse undergoes decomposition within these landfill sites, it generates methane gas—a highly potent greenhouse gas (United State Environmental Protection Agency, 2024).

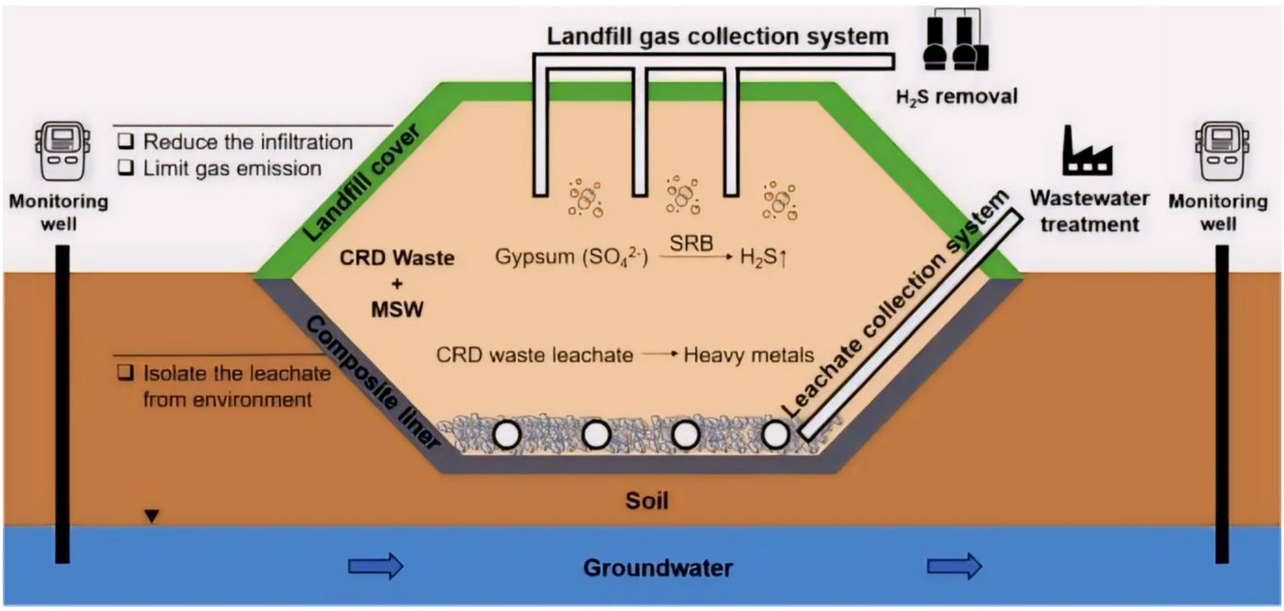

FIGURE 3
The leachates in waste landfill (Chen et al., 2022).

Over a century, the heat-trapping capacity of methane has been 28–36 times more efficacious than that of carbon dioxide, thus exacerbating climate change and adversely impacting the atmospheric equilibrium (United State Environmental Protection Agency, 2024) and contributing to climate change. Furthermore, Landfills can contaminate groundwater and soil with hazardous chemicals and pollutants, harming human health and wildlife. However, landfills can negatively impact the environment and human health, with one major problem being leachate (Bausback, 2016b). Leachate is a liquid that forms when landfill waste breaks down, and water filters through that waste and picks up toxins. Rain falling on the top of the landfill is the most significant contributor to leachate, and groundwater entering the landfill can also produce leachate. This liquid can contaminate groundwater and soil with hazardous chemicals and pollutants, harming human health and wildlife (Iravanian and Ravari, 2020).

Another environmental benefit of concrete recycling is reducing greenhouse gas emissions. The recycling process generates fewer emissions than producing new concrete and conserves natural resources, such as water, minerals, and energy, used to make new concrete. Mitigating the environmental impact of landfills involves strategies to reduce waste volume and manage leachate. Recycling concrete, for example, can help by reducing the volume of waste directed to landfills and subsequently decreasing the production of leachate (Bausback, 2016a). Concrete recycling not only prevents additional waste from entering landfills but also mitigates the formation of methane by reducing organic material.

This process generates fewer greenhouse gas emissions compared to producing new concrete and conserves natural resources like water, minerals, and energy that would otherwise be used in the production of new concrete (N. R. Association, 2018). Consequently, recycling efforts contribute to minimizing landfill-related contamination and mitigating the negative environmental impacts associated with landfill waste (U. S. Agency, 2024).

3.3.2 Economic and social benefits of concrete recycling

Concrete recycling presents a combination of direct environmental and indirect economic benefits. One notable advantage is the potential for job creation within the recycling industry, which not only stimulates local economies but also improves the livelihoods of individuals in the community. According to the National Solid Waste Strategy in Jordan, the formalization of the informal waste recycling and materials recovery sector is viewed as an economic opportunity to sustain landfill infrastructure and improve the livelihoods of many impoverished individuals (Dwarkasing, 2019).

A practical example of these benefits can be seen in the case of São Sebastião in Brazil. Here, the informal waste sector has been successfully integrated into the formal economy, yielding significant social, economic, and environmental advantages. Waste pickers, known locally as "catadores," have organized into cooperatives, receiving formal recognition and support from both public and private entities. This shift has resulted in improved income, better working conditions, and significant poverty reduction (Lima and Mancini, 2017). The integration has also fostered economic stability and social inclusion for these typically marginalized groups.

Environmentally, the contributions of the catadores have been substantial. Their efforts in efficient waste collection, sorting, and recycling help preserve resources and reduce landfill usage, thereby lowering greenhouse gas emissions. Furthermore, these activities promote community education on sustainable waste management practices (Lima and Mancini, 2017). The São Sebastião case exemplifies how the transformation of informal sectors can lead to impactful contributions to local economies and environmental sustainability.

In conclusion, concrete recycling significantly reduces landfill use and greenhouse gas emissions while providing a range of hybrid environmental and economic benefits. These include resource conservation, job creation, and the formal integration of informal waste sectors, all of which contribute to the enhancement of local economies and the promotion of environmental sustainability.

3.4 Jordan in the light of global perspective

Concrete recycling, a critical aspect of sustainable waste management, has seen varying degrees of implementation and success in countries worldwide, offering insights that might apply to Jordan. Recycling concrete from construction, demolition, and renovation projects is essential for mitigating environmental risks. However, the need for more recycling facilities often hampers enforcing laws to produce recycled aggregates (Atta and Bakhoum, 2023). An essential consideration in the environmental feasibility of concrete recycling is the transportation distance between demolition and construction sites; a study suggests that keeping this distance under 70 km is crucial for maintaining environmental benefits (Atta and Bakhoum, 2023).

Globally, Japan is one of the best countries adopting construction waste because they have implemented strict regulations for construction and demolition waste, including concrete waste. As a result, the country has a well-established recycling infrastructure, with many recycling facilities dedicated to concrete waste (Oh et al., 2021), and countries like Korea have demonstrated a growing emphasis on using recycled coarse aggregates in concrete, driven by increasing societal awareness of the need to conserve natural resources and efficiently use concrete waste materials (Singh et al., 2021).

This global trend is echoed in the Middle Eastern context, where countries like Egypt have been exploring the recycling of concrete construction and demolition waste for reuse in on-site applications. This practice could be extended to other countries in the region, including Jordan (Hassanein and Ezeldin, 2013). Notably, construction waste production, particularly in Middle Eastern Arab countries, has significantly risen over the past few decades, highlighting the urgency of adopting effective waste management strategies such as concrete recycling (Ibrahim et al., 2022).

Another example of using recycled concrete waste is in Florida, USA; in 2013, an artificial coral reef was constructed using pieces of concrete and some old culvert pipes from a local airport and contracting company. These components were utilized to build an artificial coral reef. In addition, they were arranged so that fish could use them readily to shelter themselves from predators and serve as a home for various marine creatures (Pumping, 2020).

In recent years, the United States has taken significant strides to prioritize sustainable construction practices, particularly in mobile crushing plants and on-site concrete recycling (Roh et al., 2020). The growing demand for eco-friendly building solutions and the need to reduce construction waste has shifted toward these innovative methods (Roh et al., 2020). The USA aims to reduce environmental impact, save resources, and contribute to the circular economy by adopting mobile crushing plants and on-site concrete recycling (Huang et al., 2018).

These international and regional examples provide a framework that Jordan might consider in evaluating the feasibility and practicality of concrete recycling. Factors such as local recycling facility availability, transportation logistics, and the economic impact of using recycled vs. natural aggregates must be assessed. Furthermore, the success of such initiatives depends on societal awareness and supportive regulatory frameworks, critical elements for the effective implementation of concrete recycling programs.

3.5 Integration of circular principles

This study's results on concrete waste management in Jordan provide a crucial foundation for integrating the R-ladder (Refuse, Reduce, Reuse, Repair, Recycle) and Circular Economy (CE) models into the nation's construction sector. Circularity refers to an economic system aimed at minimizing waste and making the most of resources. This model represents a shift away from a traditional linear economy, which follows a "take, make, dispose" model of production, toward an economy that is restorative and regenerative by design.

The R-Ladder framework is particularly relevant as it advocates for a hierarchy of actions, transitioning from reactive to proactive measures and emphasizing continual improvement and adaptation. It encourages prioritizing waste prevention strategies (Reuse, Reduce) before considering waste management options (Reuse, Repair, recycling). In Jordan's context, where only 7% of solid waste is recycled, and environmental degradation from concrete waste is prominent, applying this framework can be transformative.

Our findings highlight the urgent need for improved waste management practices in Jordan, particularly in concrete recycling. The R-Ladder's lowest step, recycling, is critical in this context. Recycling addresses immediate waste management concerns and sets the stage for higher-level strategies, such as reuse and reduction. The successful implementation of concrete recycling in Jordan could serve as a model for the broader adoption of circular economy principles in the region.

However, integrating the R-Ladder and CE models into Jordan's construction industry requires systemic change. Moving away from waste generation and toward a more sustainable approach involves more than just technological and infrastructural adjustments; it requires a shift in mindset and policies. Effective execution of such a project necessitates involvement from all national sectors, including government, local communities, and private industries. Our study suggests that each of these sectors has a unique role in creating a conducive environment for comprehensive concrete recycling initiatives.

Governmental bodies can provide regulatory support and incentives, local communities can contribute to raising public awareness and participation, and private industries can invest in the necessary technologies and infrastructures. Furthermore, aligning these efforts with global best practices and lessons learned from other countries can enhance the viability and effectiveness of the transition toward a circular economy.

Based on our study's results, this discussion opens avenues for extensive follow-up research. The broader implications of integrating the R-ladder and CE models into Jordan's construction sector, particularly how these approaches can be scaled up from recycling to more advanced steps like reducing and reusing, are beyond this paper's scope. Future research could explore these aspects, providing a more comprehensive roadmap for Jordan's journey toward a sustainable, circular economy.

4 Conclusion

The study on concrete waste management in Jordan has revealed a significant link between current waste management deficiencies and the potential for considerable environmental, social, and economic benefits through advanced recycling practices. The existing scenario, with a recycling rate of just 7%, contributes to environmental degradation and overburdened landfills, missing out on a crucial opportunity for sustainable development. The pursuit of concrete recycling in Jordan, despite its challenges, offers a viable route to addressing these issues. It requires a comprehensive strategy that includes enhancing technical skills, mobilizing economic investments, and increasing public awareness. Successful recycling initiatives promise numerous benefits: environmentally, by reducing landfill dependency and greenhouse gas emissions; socially, by improving public health and creating jobs; and economically, by aligning with global sustainable development goals.

Progressing toward improved concrete waste management in Jordan is a complex but achievable goal. It demands collaboration among government agencies, the private sector, academia, and the community. Learning from regions that have successfully integrated concrete recycling can provide valuable insights. This research underscores the urgent need for Jordan to adopt more sustainable and efficient waste management practices, which is crucial for the country's environmental preservation and sustainable development, paving the way for a more prosperous, resilient, and eco-conscious future.

The strategic blueprint presented in this study outlines the steps necessary for Jordan's transition to a more sustainable construction industry. By adopting these strategies, Jordan can conserve natural resources, reduce waste, and develop a circular economy that benefits all societal sectors. The defined roles for government, community, and private sector participation highlight the comprehensive approach needed to unlock the potential of concrete recycling within Jordan's unique socio-economic and environmental context.

The government plays a crucial role in establishing and enforcing a regulatory framework that encourages sustainable construction practices, including concrete recycling. This involves setting up regulations that promote recycling, such as providing tax incentives and subsidies for companies investing in recycling facilities. Additionally, government support for research and development, along with public awareness campaigns about the benefits of concrete recycling, is essential.

Collaborating with private entities can expedite the development of recycling infrastructure and engage regional communities in waste management initiatives. Providing access to necessary equipment and facilities will also drive innovation and efficiency in recycling efforts. Policies that mandate the use of recycled materials in construction projects can further demonstrate the government's commitment to sustainability.

Community involvement is equally important in fostering a recycling culture. Educational campaigns can raise awareness about the benefits of concrete recycling and encourage public participation in recycling programs. Building networks with local businesses, schools, and community organizations can create a collaborative framework for recycling initiatives, expanding their reach and impact. Social organizations also play a key role in organizing events like recycling drives and cleanup campaigns, which promote recycling and involve the community in sustainable practices.

The private sector has the resources and capacity to significantly advance the concrete recycling industry. By creating a market for recycled concrete products and advocating their use in construction projects, the private sector can drive the adoption of eco-friendly building practices. Collaboration with research institutions and experts can facilitate the exchange of knowledge and best practices, leading to the development of innovative technologies and more efficient recycling methods. Supporting research and development initiatives further enhances the recycling sector, promoting sustainable waste management practices.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

MA-S: Conceptualization, Data curation, Formal analysis, Methodology, Resources, Writing – original draft. BG: Conceptualization, Project administration, Supervision, Validation, Writing – review & editing. MR: Conceptualization, Funding acquisition, Investigation, Methodology, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

References

Abu Hajar, H., Al-Qaraleh, L., Moqbel, S., and Alhawarat, A. (2021). Prospects of sustainable waste management in developing countries: a case study from Jordan. *Environ. Monit. Assess.* 193:732. doi: 10.1007/s10661-021-09522-z

Abu Hajar, H., Tweissi, A., Abu Hajar, Y. A., Al-Weshah, R., Shatanawi, K. M., Imam, R., et al. (2020). Assessment of the municipal solid waste management sector development in Jordan towards green growth by sustainability window analysis. *J. Clean. Prod.* 258, 1–13. doi: 10.1016/j.jclepro.2020.120539

Abu-Qdais, H., Shatnawi, N., and Al-Shahrabi, R. (2023). Modeling the impact of fees and circular economy options on the financial sustainability of the solid waste management system in Jordan. *Resources* 12:32. doi: 10.3390/resources12030032

Alawneh, R., Ghazali, F., Ali, H., and Sadullah, A. (2019). A Novel framework for integrating United Nations Sustainable Development Goals into sustainable non-residential building assessment and management in Jordan. *Sust. Cities Soc.* 49:101612. doi: 10.1016/j.scs.2019.101612

Alkhraisha, A. (2023). The implications of construction and demolition waste management in Jordan. *Environm. Ecol. Res.* 11, 249–273. doi: 10.13189/eer.2023.110203

Al-rifai, J., and Amoudi, O. (2016). Understanding the key factors of construction waste in Jordan. *Jordan J. Civil Eng.* 10, 244–253. doi: 10.14525/JJCE.10.1.3540

Alshdiefat, A. S., Sharif, A. A., Alharahsheh, A. I., Albrka, S. I., Olsson, N., Younes, M., et al. (2023). "Construction and demolition waste management in Jordan: a multifaceted perspective," in *Construction Innovation* (Amsterdam: Elsevier).

Atta, I., and Bakhoum, E. (2023). Environmental feasibility of recycling construction and demolition waste. *Int. J. Environm. Sci. Technol.* 21, 2675–2694. doi: 10.1007/s13762-023-05036-y

Attia, T. (2020). Towards a national strategy for CandD waste management in Egypt. *J. Al-Azhar Unive. Eng. Sect.* 42, 191—209.

Atyyat, F. (2020). *In Jordan, Governmental Measures are Limited to Solid Waste, ALBEIT SHY INITIATIVES FOR Sorting and Recycling*. Berlin: Heinrich-Böll-Stiftung. Available online at: https://ps.boell.org/en/2020/09/29/jordan-governmental-measures-are-limited-solid-waste-albeit-shy-initiatives-sorting-and (accessed October 7, 2020).

Bausback, B. (2016a). Leachate management and treatment in landfills. *J. Environm. Eng.* 2016, 401—412.

Bausback, B. (2016b). *The 3 Most Common Landfill Problems and Solutions (HANDEX)*. Available online at: https://www.hcr-llc.com/blog/the-3-most-common-landfill-problems-solutions

Carrington, D. (2016). *Increase Crime Rates and Become a Haven for Criminal Activity*. Available online at: https://www.theguardian.com/environment/2016/sep/22/ea-chief-waste-is-the-new-narcotics (accessed December 22, 2023).

Cementra (2018). *Who We Are*. Available online at: http://cementra.com/en/about/who-we-are (accessed March 3, 2024).

Chen, Z., Feng, Q., Yue, R., Chen, Z., Moselhi, O., Soliman, A., et al. (2022). Construction, renovation, and demolition waste in landfill: a review of waste characteristics, environmental impacts, and mitigation measures. *Environ. Sci. Pollut. Res.* 29:5. doi: 10.1007/s11356-022-20479-5

Cove.tool (2023). *Green Concrete: The Choice for Modern Construction*. Available online at: https://cove.tools/blog/bim-green-concrete-the-choice-for-modern-construction (accessed December 7, 2023).

Dwarkasing, C. (2019). *International Cooperation Improves Wastepickers' Conditions, North-Eastern Jordan*. Available online at: https://ejatlas.org/print/wastepickers-face-better-conditions-due-to-international-cooperation-efforts-in-north-eastern-jordan (accessed December 26, 2019).

Ellen MacArthur Foundation (2013). "Towards the circular economy Vol. 1: an economic and business rationale for an accelerated transition," in *Ellen MacArthur Foundation*. Available online at: https://www.ellenmacarthurfoundation.org/towards-the-circular-economy-vol-1-an-economic-and-business-rationale-for-an (accessed October 16, 2023).

EPA (1992). "SW-846 test method 1311: toxicity characteristic leaching procedure," in *EPA, Uniteds State Environmental Protection Agency*. Available online at: https://www.epa.gov/sites/default/files/2015-12/documents/1311.pdf (accessed December 11, 2023).

EPA (1999). "Construction site chemical control," in *EPA, United State Environmental Protection Agency*. Available online at: https://www3.epa.gov/npdes/pubs/ch4-3b.htm (accessed October 4, 1999).

EPA (2024). *Landfill Methane Outreach Program (LMOP)*. Available online at: https://www.epa.gov/lmop/basic-information-about-landfill-gas (accessed April 25, 2024).

EPA United State environmental Protection Agency (2023). *Recycling Economic Information (REI) Report. Retrieved November 2020, from EPA United State environmental Protection agency*. Available online at: https://www.epa.gov/smm/recycling-economic-information-rei-report (accessed August 4, 2023).

Estévez, B. A. (2006). "Environmental impact of concrete recycling, coming from construction and demolition waste (C and DW)," in *Environmental Science* (Amsterdam: Elsevier).

Eurupean Commission (2022). *Fibre Reinforced Concrete with Recycled and Waste Materials Optimised for Improved Sustainability of Urban Projects. (CORDIS EU research results)*. Available online at: https://cordis.europa.eu/article/id/436557-green-material-solutions-for-sustainable-construction (accessed May 17, 2022)

Farhat, S. (2018). *What a Waste: An Updated Look into the Future of Solid Waste Management. (World Bank)* Washington, D.C.: The World Bank. Available online at: https://www.worldbank.org/en/news/immersive-story/2018/09/20/what-a-waste-an-updated-look-into-the-future-of-solid-waste-management, (accessed September 20, 2018)

Ganiron, Y. U. (2015). Recycling concrete debris from construction and demolition waste. *Int. J. Adv. Sci. Technol.* 2, 7–24. doi: 10.14257/ijast.2015.77.02

GCR Staff (2020). *Five-year Study Shows Recycled Concrete Works as Well as Normal Concrete, Maybe a Bit Better*. London: Global Constructionre View. Available online at: https://www.globalconstructionreview.com/five-year-study-shows-recycled-concrete-works-well/ (accessed December 9, 2020).

Ghisellini, P. C. (2016). A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems. *J. Clean. Prod.* 114, 11–32. doi: 10.1016/j.jclepro.2015.09.007

Ghorbani, S., Sharifi, S., Ghorbani, S., Tam, V., de Brito, J., and Kurdo, R. (2019). Effect of crushed concrete waste's maximum size as partial replacement of natural coarse aggregate on the mechanical and durability properties of concrete. *Conserv. Recycl. Res.* 149, 664–673. doi: 10.1016/j.resconrec.2019.06.030

GIZ (2014). "Country report on the solid waste management in JORDAN," in *German Retech Partnrtship*. Amman: GIZ.

GIZ (2021). *Climate and Employment Impacts of Sustainable Building Materials in the Context of Development Cooperation*. Bonn: Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH.

Goggins, J. (2024). *Green Cement Production is Scaling Up – and it Could Cut the*. Available online at: https://theconversation.com/green-cement-production-is-scaling-up-and-it-could-cut-the-carbon-footprint-of-construction-227688

Gómez-Soberón, J. M. (2002). Porosity of recycled concrete with substitution of recycled concrete aggregate - an experimental study. *Cement Concr. Res.* 32:8. doi: 10.1016/S0008-8846(02)00795-0

Hassanein, O., and Ezeldin, A. S. (2013). Concrete recycling in Egypt for construction applications: a technical and financial feasibility model. *Int. J. Environm. Chem. Ecol. Geol. Geophys. Eng.* 7, 902–907.

Huang, B., Wang, X., Kua, H., Geng, Y., Bleischwitz, R., and Ren, J. (2018). Construction and demolition waste management in China through the 3R principle. *Resour. Conserv. Recycl.* 129, 36–44. doi: 10.1016/j.resconrec.2017.09.029

Ibrahim,O., Al-Kindi, G., Qureshi, M. U., and Al Maghawry, S. (2022). Challenges and construction applications of solid waste management in middle East Arab countries. *Processes* 10:2289. doi: 10.3390/pr10112289

Indexbox (2024). *Jordan: Market for Ready-Mixed Concrete And Factory Made Mortars 2024*. Walnut, CA: Indexbox. Available online at: https://www.indexbox.io/store/jordan-ready-mixed-concrete-market-analysis-forecast-size-trends-and-insights/ (accessed March 1, 2024).

Iravanian, A., and Ravari, S. (2020). Types of contamination in landfills and effects on the environment: a review study. *Earth Environm. Sci.* 614:012083. doi: 10.1088/1755-1315/614/1/012083

Jerie, S. (2016). Occupational risks associated with solid waste management in the informal sector of Gweru, Zimbabwe. *J. Environm. Public Health* 2016, 2–14. doi: 10.1155/2016/9024160

Jomaa, B. (2023). *An Overview of the Middle East Construction Material Market*. Available online at: https://www.linkedin.com/pulse/overview-middle-east-construction-material-market-bilal-jomaa/ (accessed September 15, 2023).

Keith, W., and Anderson, J. S. (2009). *Use of Recycled Concrete Aggregate in PCCP: Literature Search*. Spokane, WA: Washington State Department of Transportation. Available online at: https://www.wsdot.wa.gov/research/reports/fullreports/726.1.pdf (accessed June 26, 2023).

Kim, Y.-H., Park, C., Choi, B., Shin, T., Jun, Y., and Kim, J. (2020). Quantitative measurement of water absorption of coarse lightweight aggregates in freshly-mixed concrete. *Int. J. Conc. Struct. Mater.* 14:408. doi: 10.1186/s40069-020-00408-x

Kizuna (2022). *Carbon-Negative Concrete: A Game Changer for a Sustainable Future*. Available online at: https://www.japan.go.jp/kizuna/_userdata/pdf/2022/autumn2022/carbon-negative_concrete.pdf (accessed August 29, 2022).

Kooshian, C. (2023). *Compendium on GHG Baselines and Monitoring Passenger and Freight Transport*. Bonn: UNFCCC, United Nations Framework Convention on Climate Change.

Kou, S. C. (2012). Enhancing the durability properties of concrete prepared with coarse recycled aggregate. *Const. Build. Mater.* 35, 69–76. doi: 10.1016/j.conbuildmat.2012.02.032

Lima, N., and Mancini, S. (2017). Integration of informal recycling sector in Brazil and the case of Sorocaba City. *Waste Manage. Res.* 35, 721–729. doi: 10.1177/0734242X17708050

Liu, H., Hua, M., Zhu, P., Chen, C., Wang, X., Qian, W., et al. (2021). Effect of freeze–thaw cycles on carbonation behavior of three generations of repeatedly recycled aggregate concrete. *Appl. Sci.* 11:2643. doi: 10.3390/app11062643

Malešev, M., Radonjanin, V., and Marinković, S. (2011). Recycled concrete as aggregate for structural concrete production. *Sustainability* 3, 465–468. doi: 10.3390/su3020465

Manaseer, C. I. (2020). *Company History*. Available online at: https://www.manaseergroup.com/Cement/ (accessed March 2, 2024).

Manfredi, S., Tonini, D., Christensen, T. H., and Scharff, H. (2009). Landfilling of waste: accounting of greenhouse gases and global warming contributions. *Waste Manag. Res.* 27, 825–836. doi: 10.1177/0734242X09348529

Minister of Industry in Canda (2022). *Roadmap to Net-Zero Carbon Concrete by 2050*. Available online at: https://ised-isde.canada.ca/site/clean-growth-hub/en/roadmap-net-zero-carbon-concrete-2050 (accesssed November 9, 2022).

Ministry of Environment (2020). *The Waste Management Framework Law No.16 of 2020*. Available online at: https://www.moenv.gov.jo/ebv4.0/root_storage/ar/eb_list_page/waste_management_framework_law_no_16_of_2020.pdf (accessed January 14, 2024).

Ministry of the Environment (2014). *History and Current State of Waste Management in Japan*. Available online at: https://www.env.go.jp/content/900453392.pdf (accessed February 15, 2024).

Municipality Greater Amman (2020). *Advancing Jordan's Solid Waste Management System*. Fairfax, VA: CDM Smith. Available online at: https://www.cdmsmith.com/en-EU/Client-Solutions/Projects/Solid-Waste-Management-Jordan (accessed January 9, 2024).

Nilimaa, J. (2023). Smart materials and technologies for sustainable concrete construction. *Dev. Built Environm.* 15:100177. doi: 10.1016/j.dibe.2023.100177

N. R. Association (2018). *Environmental Benefits of Concrete Recycling*. Available online at: https://www.nrmca.org/sustainability/environmental-benefits-concrete-recycling (accessed February 11, 2024).

Oh, D., Noguchi, T., Kitagaki, R., and Chai, H. (2021). Proposal of demolished concrete recycling system based on performance evaluation of inorganic building materials manufactured from waste concrete powder. *Renew. Sust. Energy Rev.* 135:110147. doi: 10.1016/j.rser.2020.110147

Oxford Business Group (2018). *New Labour Pool and Higher Standards to Help Jordan's Construction Sector Meet Increasing Demand*. Aqaba: Oxford Business Group.

Pacheco-Torgal, F., and Jalali, S. (2010a). Compressive strength and durability properties of ceramic wastes based concrete. *Mater. Struct.* 44, 155–167. doi: 10.1617/s11527-010-9616-6

Pacheco-Torgal, F., and Jalali, S. (2010b). Reusing ceramic wastes in concrete. *Const. Build. Mater.* 24, 832–838. doi: 10.1016/j.conbuildmat.2009.10.023

Pedro, D., De Brito, J., and Evangelista, L. (2014a). Influence of the use of recycled concrete aggregates from different sources on structural concrete. *Const. Build. Mater.* 71, 141–151. doi: 10.1016/j.conbuildmat.2014.08.030

Pedro, D., De Brito, J., and Evangelista, L. (2014b). Performance of concrete made with aggregates recycled from precasting industry waste: influence of the crushing process. *Materi. Struct.* 47, 804–815.

Poole, C. J. M., and Basu, S. (2017). Systematic Review: Occupational illness in the waste and recycling sector. *Occup. Med.* 67, 626–636. doi: 10.1093/occmed/kqx153

Pumping, D. C. (2020). *What is Recycled Concrete Used For*? Jacksonville: Dynamic Concrete Pumping. Available online at: https://www.dcpu1.com/blog/recycled-concrete-uses/ (accessed February 17, 2020).

Reis, G. S. (2021). Current applications of recycled aggregates from construction and demolition: a review. *Matirelas* 14:1700. doi: 10.3390/ma14071700

Rincon, L., Moscoso, Y. M., Hamami, M., Matos, J., and Bastidas-Arteaga, E. (2024). Degradation models and maintenance strategies for reinforced concrete structures in coastal environments under climate change: a review. *Buildings* 14:562. doi: 10.3390/buildings14030562

Rodrigo-Ilarri, J., Rodrigo-Clavero, M. E., Romero, C. P., and Suárez-Romero, P. (2022). Do solid waste landfills really affect land use change? Answers using the weighted environmental Index (WEI). *Remote Sens.* 14:5502. doi: 10.3390/rs14215502

Roh, S., Kim,. R., and Park, W., Ban, H. (2020). Environmental evaluation of concrete containing recycled and by-product aggregates based on life cycle assessment. *Appl. Sci.* 10, 2–13. doi: 10.3390/app10217503

Saidan, M., and Drais, A. (2016). *Your Guide to Waste Management in Jordan Waste Sorting Informative booklet*. Amman, Jordan: Jordan Green Building Council.

Schneider, M. (2019). The cement industry on the way to a low-carbon future. *Cement Concrete Res.* 124:105792. doi: 10.1016/j.cemconres.2019.105792

Sheldon, T. (2023). *UN Report Highlights Bamboo's Role in the Shift to Bio-Based Building Materials*. Available online at: https://www.bamcore.com/post/un-report-highlights-bio-based-building-materials (accessed September 13, 2023).

Shima, H., Tateyashiki, H., Matsuhashi, R., and Yoshida, Y. (2005). An advanced concrete recycling technology and its applicability assessment through input-output analysis. *J. Adv. Concr. Technol.* 3, 53–67. doi: 10.3151/jact.3.53

Silva, R., de Britto, J., and Dhir, R. K. (2014). Properties and composition of recycled aggregates from construction and demolition waste suitable for concrete production. *Const. Build. Mater.* 65, 201–217. doi: 10.1016/j.conbuildmat.2014.04.117

Singh, M., Danie Roy, D., Washeem, S., and Singh, H. (2021). Feasibility and performance analysis of carbonated recycled aggregate concrete. *Int. J. Sust. Eng.* 14, 761–775. doi: 10.1080/19397038.2020.1856967

Sivakrishna, A., Adesina, A., Awoyera, P. O., and Rajesh Kumar, K. (2020). "Green concrete: a review of recent developments," in *Materials Today: Proceedings* (Amsterdam: Elsevier), 54–58.

Souza, E. (2020). *Is It Possible to Recycle Concrete*? Available online at: https://www.archdaily.com/933616/is-it-possible-to-recycle-concrete (accessed February 17, 2020).

Sustainability Me News (2023). *Insight: Middle East Leads the Way in Creating Sustainable Built Environments*. Available online at: https://www.sustainabilitymenews.com/construction/insight-middle-east-leads-the-way-in-creating-sustainable-built-environments (accessed Seotember 12, 2023).

Tafesse, S., Girma, Y., and Dessalegn, E. (2022). Analysis of the socio-economic and environmental impacts of construction waste and management practices. *Heliyon* 8, 1–10. doi: 10.1016/j.heliyon.2022.e09169

Tam, V. W. (2005). Microstructural analysis of recycled aggregate concrete produced from two-stage mixing approach. *Cement Concr. Res.* 35, 1195–1203. doi: 10.1016/j.cemconres.2004.10.025

Thomas, B. S., Yang, J., Bahurudeen, A., Chinnu, S., Andalla, J., Hawileh, R., et al. (2022). Geopolymer concrete incorporating recycled aggregates: a comprehensive review. *Cleaner Mater.* 3:100056. doi: 10.1016/j.clema.2022.100056

Times, T. J. (2023). *Construction outputs stand at JD1.7 billion, sector employs 17,000 — JCI*. Available online at: https://jordantimes.com/news/local/construction-outputs-stand-jd17-billion-sector-employs-17000-%E2%80%94-jci%C2%A0 (accessed August 09, 2023).

Transparency Market Research (2023). *Construction Market*. Available online at: https://www.transparencymarketresearch.com/construction-market.html (accessed August 08, 2023).

U. N. Environmental Program (2020). *Environmental Management Guidelines for Debris Recycling Sites in Iraq*. Online: UN Environmental Program. Available online at: https://www.iu.edu.jo/iuthesis/search/thesis_details.php?id=594 (accessed March 02, 2024).

UNEP (2019). *Turning Waste into an asset in Aqaba, Jordan*. Available online at: https://www.unep.org/news-and-stories/story/turning-waste-asset-aqaba-jordan (accesed March 28, 2019).

United State Environmental Protection Agency (2024). *Landfill Methane Outreach Program (LMOP)*. Available online at: https://www.epa.gov/lmop/basic-information-about-landfill-gas#:$\sim$:text=Landfill%20gas%20(LFG)%20is%20a,of%20non%2Dmethane%20organic%20compounds (accessed Febrauray 12, 2024).

University of British Columbia Okanagan Campus (2020). *Recycled Concrete Could be a Sustainable Way to Keep Rubble Out of Landfill. (University of British Columbia)*. Available online at: https://www.sciencedaily.com/releases/2020/11/201130150358.htm (accessed November 30, 2023).

U. S. Agency (2024). *Greenhouse Gas Emissions and Sinks: 1990–2022*. Available online at: https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-\hbox1990--2022 (accessed February 11, 2024).

Vaverková, M., Maxianová, A., Winkler, J., Adamcová, D., and Podlasek, A. (2019). Environmental consequences and the role of illegal waste dumps and their impact on land degradation. *Land Use Policy* 89:104234. doi: 10.1016/j.landusepol.2019.104234

Wu, Z., Luo, L., Li, H., Wang, Y., Bi, G., and Afari, A. (2021). An analysis on promoting prefabrication implementation in construction industry towards sustainability. *Int. J. Environm. Res. Public Health* 18:6. doi: 10.3390/ijerph182111493

Yehia, S., Helal, K., Abusharkh, A., Zhaer, A., and Istaitiyeh, H. (2015). Strength and durability evaluation of recycled aggregate concrete. *Int. J. Conc. Struct. Mater.* 9, 219–239. doi: 10.1007/s40069-015-0100-0

Zega, C. J., and Di Maio, A. A. (2011). Use of recycled fine aggregate in concretes with durable requirements. *Waste Manage.* 31, 2336–2340. doi: 10.1016/j.wasman.2011.06.011