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Article

Fostering Circularity in the Stone Industry: Multi-Criteria Analysis of Existing Sustainable Indicators for Decision-Making Support

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Abstract

The stone industry generates substantial waste along the quarrying, cutting and finishing chain, with only about 22% of the extracted material processed into final products, while roughly 64% is lost as slurry and 8% as solid waste. Compared to other industries such as wood and steel, there is a significant gap in the exploitation of relevant circular economy indicators for the stone industry. To address such limitation, this study proposes a sector-specific indicator framework built in three stages: systematic identification of existing CE indicators through a Scopus-based literature review, further refinement against three strategies for the stone sector (materials preservation, process optimisation and reduction of risk to human well-being), together with two suitability filters based on development stage and redundancy, and finally an indicative prioritisation using a simplified Analytic Hierarchy Process (AHP) procedure implemented in Super Decisions. Seven indicators are retained as the most applicable to the sector: Energy Use, Water Consumption, Greenhouse Gas Emissions, Replacement Ratio, Generation Ratio, Upcycling Score and Product Quality Index. The Consistency Ratio is 0.070 for the criteria pairwise-comparison matrix and ranges from 0.000 to 0.010 across the six indicator pairwise-comparison matrices, reflecting the internal coherence of the deterministic scoring procedure used to derive them. The framework is presented as an initial, transparent proposal to support monitoring and resource efficiency benchmarking in the stone supply chain. Empirical validation through further industrial case studies and broader expert contribution is an essential next step.

Keywords: circular economy; stone slurry; key performance indicators; multi-criteria decision making; stone supply chain; sustainability metrics; analytic hierarchy process

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1. Introduction

The stone industry, referring to the quarrying, cutting and finishing chain that transforms natural dimension stone into blocks, slabs and finished elements for construction and architectural use [1–3], plays a key role in meeting the rising demand for natural stone in construction and architecture due to global economic growth. Unlike general manufacturing, the sector is characterised by exceptionally high mass loss between extraction and finished product, heterogeneous waste streams dominated by cutting slurry and by strong site specificity of the quarry-to-plant material flows, all of which limit the direct transferability of generic circularity metrics developed for discrete manufactured products [4,5]. Natural stone end products carry a range of benefits as well as impacts in environmental, economic and social areas [1,6]. Such repercussions challenge the sustainability competitiveness of stone materials, and even though a significant portion of solid waste is already being repurposed, the reuse and recycling of stone waste represent relatively new areas of interest, where straightforward cost–benefit analyses are still evolving [1]. The lack of established methods for the efficient collection and utilisation of waste hinders the accurate assessment of the economic and environmental advantages of such practices. Moreover, when the slurry, which is the liquid component of stone waste, is also considered, then the magnitude of the environmental impacts may include water pollution, soil contamination and air pollution. Such impacts further emphasise the crucial necessity for accurate waste characterisation and proficient management strategies, especially considering that approximately 64% of the total waste generated in the EU in 2022 [7] was classified as mineral waste.

Tackling the inefficiency of the production chain of stone can lead to the development of new materials with lower embodied carbon that can adopt the by-products of stone as secondary raw materials. Indeed, it is possible to find in the literature the initial application of the by-products of stone for the production of low-carbon cement-based materials [8–10]. By evaluating the impacts of the stone industry, it is also pertinent to investigate the possible transition from a linear to a circular approach.

Goddin et al. [11] state the urge to shift from a linear to a circular economy (CE), even if such a transition presents multiple challenges. Between 2018 and 2022, the share of secondary materials in the global economy fell from 9.2% to 7.2%, largely driven by the rising extraction of non-metallic minerals [12]. Non-metallic minerals have grown significantly and account for about half of global material extraction [12]. The stone sector is therefore correlated to the observed decline in global circularity, which indicates the development of stone-specific CE indicators as both scientifically and policy relevant.

Taking into account the significant global impact of the stone industry, as well as the growing adoption of this material in the AEC sector, this study proposes circularity and sustainability indicators tailored to the stone industry. The proposed methodology follows the identification of existing indicators through a literature database, enhanced by further refinements based on the strategies and scope of the desired evaluation and the level of development and similarities between indicators. Lastly, a final selection of indicators is reached with AHP, which is a multi-criteria decision-making method largely utilised in life-cycle assessment (LCA) studies [13]. Such identification of indicators is the main contribution of this research and can encourage policy makers and industry stakeholders to monitor stone impacts more efficiently and more transparently.

Despite the growing interest in CE indicators, no existing framework specifically addresses the circularity of stone waste throughout its life cycle. Existing indicator frameworks primarily focus on generic manufacturing or product-level applications, without accounting for the specific waste dynamics of extractive industries [4,5]. In the construction sector, several efforts have been made to link CE indicators to material flows and waste management [14,15], but stone production remains largely underexplored, despite its high material intensity and low conversion efficiency.

However, these studies seldom propose a structured, data-driven methodology to assess circular performance, nor do they address the sector's dependence on data availability, lithological diversity and regional regulatory frameworks. Consequently, the research gap lies in the absence of validated circularity indicators tailored to the stone industry's heterogeneous production processes and data constraints. Developing such a framework is essential to bridge environmental assessment tools such as LCA with CE performance measurement, enabling both quantitative evaluation and policy alignment for circular transition in the stone sector.

The main goal of this study is to identify, adapt and prioritise circularity indicators applicable to stone waste management by integrating environmental, economic and social dimensions. We also including mapping and classifying CE indicators from the literature, refining these indicators to reflect stone industry characteristics and, finally, applying the Analytic Hierarchy Process to determine the relative weighting of the criteria. Adapting general CE indicators through a multi-criteria framework can enhance their relevance and usability for stone waste management, thereby providing a sector-specific tool that complements and strengthens current sustainability assessment approaches such as LCA.

2. Literature Review

2.1. Circularity Assessment

Characterised by significant inefficiencies, with a large percentage of extracted materials turning into waste during production, the global stone production chain presents a major concern regarding the environmental impact of extraction and processing [1,6]. Indeed, as shown in Figure 1, current studies demonstrate that of the total extracted stone materials, only about 22% is processed into final products, while about 64% ends up as slurry as a by-product of either quarrying or cutting, and about 8% results in solid waste [6].

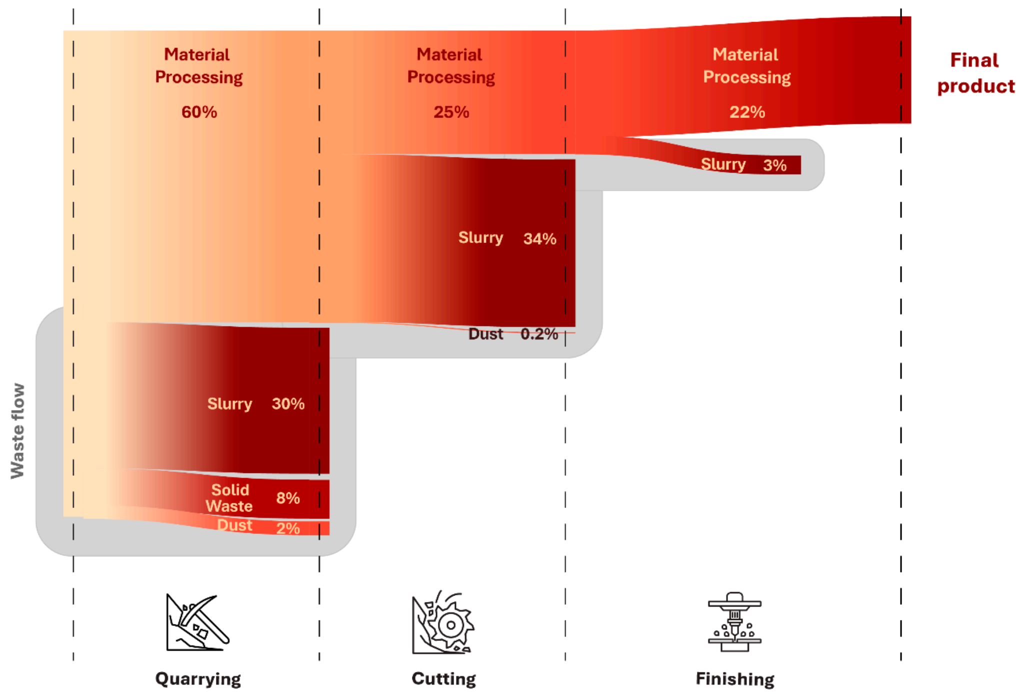

Figure 1. Schematic diagram of waste generation through stone extraction processes (quarrying, cutting and finishing) according to different types of waste (slurry, solid waste and dust), based on [1,6]. Visualisation created with Flourish V1 and Illustrator 2026.

Moreover, discussion and scientific research on stone waste, when compared to other sectors such as wood and steel, are presented relatively isolated from, and less connected to, the concepts of circularity, as highlighted in Figure 2, which provides a map clustering analysis of current studies from the Scopus database in the field of life-cycle analysis and

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circularity of building materials. The map, instead, reveals that stone and stone waste are primarily linked to the keyword "recycling", demonstrating the efforts in scientific research to push towards some recovery of stone waste through new technologies and products that can ultimately reduce the impact of such an industry.

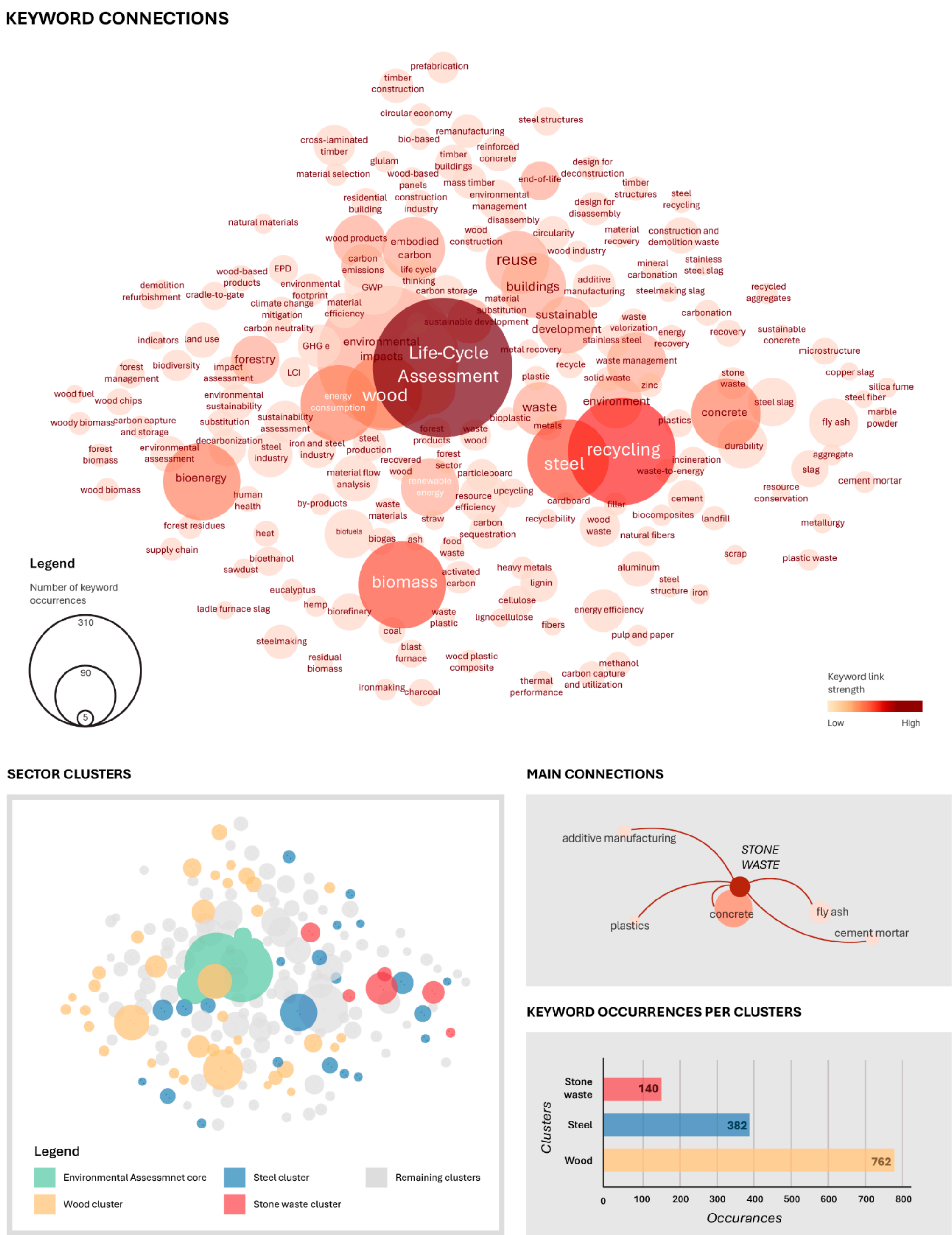

Figure 2. Map of keyword occurrences in scientific publications related to life-cycle assessment (LCA) and circularity, considering three different sectors—wood, steel and stone waste—based on Scopus query: TITLE-ABS-KEY ("stone waste" AND replacement) OR ("stone waste" AND lca) OR ("stone waste" AND "circular economy") OR ("stone slurry" AND lca) OR ("stone slurry" AND "circular economy") OR ("stone slurry" AND replacement) OR ("stone dust" AND replacement) OR ("stone dust" AND lca) OR ("stone dust" AND "circular economy") OR ((wood OR timber OR steel) AND replacement) OR ((wood OR timber OR steel) AND lca) OR ((wood OR timber OR steel)AND "circular economy"). Other queries were used, with different stone industry term iterations, but only the most representative one is displayed. Visualisation created with VOS Viewer 1.6.21 and Illustrator 2026.

Furthermore, Figure 2 shows that the word "stone waste" does not present any direct connection to circularity or LCA, demonstrating a potential gap in terms of studies in this field. Instead, the main connection of stone waste is with the keyword "concrete", indicating the general tendency to relate the reuse of stone with cementitious materials.

The Scopus database was chosen for its broad peer-reviewed coverage of engineering, construction and life-cycle assessment journals and for its compatibility with VOS Viewer. Search strings were developed iteratively from three seed concepts (stone waste, LCA and circular economy) and expanded through synonyms identified in preliminary reading such as "stone slurry" and "stone dust". The final string used to build Figure 2 is reported in the figure caption. The search covered the period 1994–2024, was restricted to English-language documents of the type Article or Review and returned 4400 documents and 4426 occurrences of the keywords in total.

2.2. Data Assessment on the Stone Sector

Going further regarding the evaluation of LCA, it is also relevant to consider CE, which is a well-regarded concept that has been extensively explored in terms of its conceptual framework and definitions. However, it continues to be open to an array of interpretations and discussions. At present, the literature offers a multitude of definitions for CE. For instance, ref. [16] describes CE as a system that moves away from the conventional focus on disposal to instead emphasise the minimisation of waste and the maximisation of resources over multiple life cycles. Such a model promotes reducing, reusing, recycling and recovering materials throughout the stages of production, distribution and consumption. It also operates at different levels: The micro level focuses on individual products, companies and consumers. The meso level targets structures like eco-industrial parks, and the macro level encompasses broader entities such as cities, regions or entire countries. The primary aim of this approach is to support sustainability through a balance between environmental health, economic prosperity and social well-being, benefitting both present and future generations.

According to Circle Economy [12], CE is depicted as an economic model that concentrates on minimising, regenerating and efficiently distributing essential resources for the planet and its inhabitants. It highlights the importance of a cultural transformation that favours non-material methods of meeting needs and prioritises investment in health, wellbeing, education and quality employment rather than the accumulation of material goods. The foundation of this concept lies in principles such as reducing the use of materials, rejuvenating natural ecosystems and reallocating resources in a way that yields societal advantages while adhering to the boundaries set by nature.

Even though there is no universally accepted definition of CE, as it is subject to various interpretations, most of the definitions converge. Originating from multiple sources, it is seen as a broad concept encompassing a range of strategies and methodologies, presenting an ambiguous relationship with sustainability as well [17,18].

Current methods and indicators have proven insufficient for fully tracking the various aspects of CE. Often, these circularity indicators are narrowly focused on objectives or isolated activities. Therefore, there is a pressing need for more appropriate circularity indicators that can effectively cover the features of all circularity strategies [19–21].

Figure 3 presents a review of existing circularity indicators that have been developed for specific applications or sectors. These indicators can be categorised into six groups based on their common characteristics relevant to measuring aspects of circularity, summarised in Table 1.

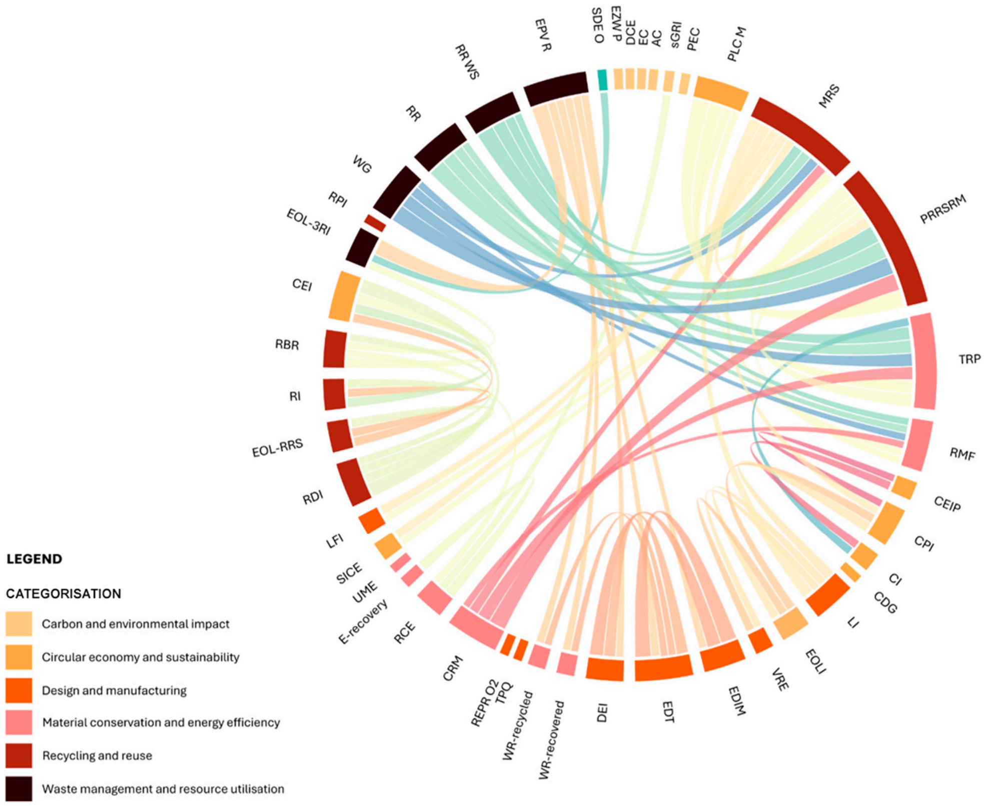

Figure 3. Circularity performance indicators based on Scopus query: TITLE-ABS-KEY ("stone waste" AND replacement) OR ("stone waste" AND lca) OR ("stone waste" AND "circular economy") OR ("stone slurry" AND lca) OR ("stone slurry" AND "circular economy") OR ("stone slurry" AND replacement) OR ("stone dust" AND replacement) OR ("stone dust" AND lca) OR ("stone dust" AND "circular economy"). Visualisation created with Flourish. See Table 2 for acronym explanation and references.

Table 1. Categorisation of the circular economy indicators reviewed in Figure 3.

Category	Description
Recycling and reuse	Desirability, potential, efficiency and environmental impact of recycling and reuse practices within the CE.
Waste management and resource utilisation	Environmental and economic impact of waste management strategies and the efficiency of recycling/recovery systems.
Circular economy and sustainability	Environmental and economic impacts across a product's life cycle within a CE framework.
Design and manufacturing	Longevity, resource efficiency and disassembly potential from a design and manufacturing perspective.
Carbon and environmental impact	Direct and indirect carbon emissions, energy consumption and the broader environmental impact of resource use.
Material conservation and energy	Efficiency of material use and energy consumption and how materials and energy are conserved, recovered and reused.

Extensive literature exists on both LCA and circularity assessments. LCA, as an established methodology, has been the focus of extensive scholarly analysis for over five decades. Concurrently, the strategies and metrics associated with circularity have also been subject to in-depth scrutiny by researchers. These investigations have methodically evaluated and classified various circularity strategies and indicators, examining their specific metrics. However, the exploration of how circularity assessment intersects with LCA remains an area that has not been comprehensively explored in scholarly research [22].

Life-cycle assessment (LCA) and circularity assessment are best understood as complementary methods rather than as substitutes [23,24]. LCA quantifies environmental impacts across a product's life cycle but does not, on its own, capture the effectiveness of circularity strategies. Conversely, circularity indicators such as the Material Circularity Indicator provide a measure of loop closure but do not translate directly into environmental performance [19,21,25]. When integrated, the two approaches provide a more complete picture, at the cost of higher assessment complexity Table 2.

Table 2. List of the circularity performance indicator acronyms used in Figure 3 and indication of their sources.

Code	Indicator	Source	Code	Indicator	Source
AC	Avoided Carbon Emissions	[26]	PLC M	Product-Level Circularity Metric	[20]
CDG	Circularity Design Guidelines	[27]	PRRSRM	Patents Related to Recycling and Secondary Raw Materials	[28]
CEI	Circular Economy Index	[29]	RBR	Recyclability Benefit Rate	[30]
CEIP	Circular Economy Indicator Prototype	[31]	RCE	Resource Conservation Efficiency	[32]
CI	Circularity Index	[33]	RDI	Recycling Desirability Index	[34]
CPI	Circularity Potential Indicators	[35]	REPR	Remanufacturing Product Profiles	[36]
CRM	Contribution of Recycled Materials to Raw Materials Demand	[20]	RI	Recycling Indices	[37]
DCE	Direct Carbon Emissions	[26]	RMF	Recycled Material Fraction	[38]
DEI	Disassembly Effort Index	[39]	RPI	Reuse Potential Indicator	[40]
EC	Embodied Carbon Emissions	[26]	RR	Recycling Rates	[20]
EDIM	Ease of Disassembly Metric	[41]	RR WS	Recycling/Recovery for Specific Waste Streams	[20]
EDT	Effective Disassembly Time	[42]	SDE O	Sustainable Design and End- of-Life Options	[43]
EOL- RRS	End-of-Life Recycling Rates	[44]	sGRI	Global Resource Indicator	[45]
EOL-3RI	End-of-Life Indices	[46]	SICE	Sustainability Indicators in EC	[47]
EOLI	End-of-Life Index	[48]	TPQ	Typology for Quality Properties	[49]
EPV R	End-Of-Use Product Value Recovery	[50]	TRP	Total Restored Products	[51]
E-recovery	Energy Recoverability	[50]	UME	Upstream Material Efficiency	[52]
EZW P	Model of Expanded Zero-Waste Practice	[53]	VRE	Value-Based Resource Efficiency	[29]
LFI	Linear Flow Index for Product Families	[47]	WG	Waste Generation	[20]
LI	Longevity Indicator	[54]	WR-recycled	Weight Recovery (for Product Recycled)	[55]
MRS	Material Reutilisation Score	[56]	WR-recovered	Weight Recovery (for Product Recovered)	[55]
PEC	Primary Energy Consumption	[57]			

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Furthermore, it is important to translate the assessment parameters and results into meaningful environmental impacts. Such translation is performed through characterisation factors, which are crucial to quantify the extent to which a certain emission or resource use contributes to a specific environmental issue. The conversion from processes to impacts should be applied by normalising, weighting and combining the impacts into a broader, more comprehensive end effect.

Current methods and indicators have proven insufficient for fully tracking the various aspects of CE. Often, these circularity indicators are narrowly focused on objectives or isolated activities. For example, overlooking factors like energy usage and pollutant emissions in these indicators can lead to a partial understanding of a system's environmental impact. Therefore, more appropriate circularity indicators that can effectively cover the features of all circularity strategies are needed.

3. Methodology

It is imperative to understand the existing gap of current methodologies for evaluating sustainability and environmental impacts within the stone industry, especially in transitioning from linear to circular sustainability assessments. Recognising the urgency of this issue, the assessment of stone waste must go beyond environmental measures, reaching for sustainability levels of resources, economy and societal dimensions, aligning with the overarching goals of CE.

The investigation of slurry originated from the stone industry comprehends the identification of its main characteristics that could contribute to a wider shift towards sustainable and circular waste management methods within the industry. This research seeks to surmount the limitations inherent in traditional LCA methodologies by defining specific indicators, establishing evaluation methodologies, and identifying requisite data, which might facilitate a comprehensive assessment of various strategies and the respective contributions to circularity within the stone industry.

In order to refine the indicators presented in the literature review to the application to the stone sector, they are initially selected based on common characteristics relevant to measuring aspects of circularity, according to three main strategies: materials preservation, optimisation of processes and risk to human well-being.

The first strategy emphasises the reduction, recycling and reuse of stone slurry to conserve materials for other purposes and to save water within the stone industry itself. It involves the minimisation of slurry generation. The optimisation of processes strategy is centred on minimising the amount of waste sent to landfills, with the objective of reaching optimal recycling and reuse of waste materials and enhancing the efficiency of the treatment stages, also reducing the presence of hazardous materials in the stone slurry composition. The last strategy questions the treatment of slurry and how it can be hazardous to human health.

The refinement from Table 3 to the fourteen actionable indicators followed two sequential filters. First, indicators still at the conceptual stage, i.e., defined in the literature without either an operational computational framework or a validated application to a comparable sector, were excluded, since their application to the stone sector cannot be supported by existing data. Second, indicators measuring the same physical or economic quantity as another with only minor differences in normalisation were merged into the most general formulation.

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Table 3. Actionable indicators for the stone waste industry, as per methodology previously defined in Section 3. References according to Figure 3 and Table 2.

Indicator	Objective	Category	Measurement
Recycling Ratio	Percentage of recycled material—slurry (recycled slurry/total slurry generated)	Environmental Resource Preservation	Quantitative
Collection Efficiency	Percentage of generated material—slurry—that is able to be collected (collected slurry/total slurry generated)	Environmental Resource Preservation	Quantitative
Separation Efficiency	Percentage of valuable components that are able to be extracted from the material—slurry (resources or nutrients extracted/target resources or nutrients in slurry)	Resource Preservation	Quantitative
Nutrient Recovery	Nutrients recovered as fertilisers or chemicals (resources or nutrients extracted/total amount of slurry)	Resource Preservation	Quantitative
Water Consumption	Reduction in water consumption due to reuse of the water content found in the material—slurry (reused water derived from slurry/total water consumption in material production)	Environmental Resource Preservation Socioeconomic	Quantitative
Water Reuse Efficiency	Percentage of water content that was able to be reused (reused water from slurry/total water content of slurry)	Environmental Resource Preservation Socioeconomic	Quantitative
Accident Rate	Accident rate during collection, handling and processing of material—slurry (number of accidents during slurry collection per thousand man-hours)	Socioeconomic	Quantitative
Recycling Toxicity Rate	Rate of increase in respiratory, eye and skin diseases due to long contact with material—slurry (number of reported diseases during slurry recycling per thousand man-hours)	Socioeconomic	Quantitative
Disposal Toxicity Rate	Toxic effects of landfilling the material—slurry (LCA for disposal: environmental and health impacts from landfilling per toxicity level of slurry)	Environmental	Quantitative
Landfill and Disposal Percentage	Percentage of material—slurry—landfilled (amount of slurry landfilled/total generated slurry)	Resource Preservation	Quantitative
Energy Use	Energy required for material—slurry—repurposing processes (energy consumption per amount of slurry)	Environmental Socioeconomic	Quantitative
GHG Emissions	GHG Emissions generated from material—slurry—processes or disposal (GHG Emissions generated from slurry per amount of slurry)	Environmental	Quantitative
Product Quality Index	Quality or purity of product made by stone slurry compared to conventional materials in terms of the product's performance in different aspects (rating—score—of product quality with recycled slurry content vs. conventional product)	Socioeconomic	Quantitative

Table 3. *Cont.*

Indicator	Objective	Category	Measurement
Replacement Ratio	The amount of materials avoided by secondary materials derived from slurry (amount of conventional materials avoided by recycled slurry/initial amount of conventional materials)	Resource Preservation Socioeconomic	Quantitative
Patents Related to Recycling and Secondary Raw Materials	Number of patented applications using slurry as a component (recycled or reused)	Socioeconomic	Quantitative
Multi-Cycling	Possibility of reusing the slurry-based product for multiple cycles (to extend the life span of the slurry)	Resource Preservation Socioeconomic	Quantitative
Energy Recovery	Energy released from slurry (Joules of energy released per amount of slurry)	Resource Preservation Socioeconomic	Quantitative
Generation Ratio	Amount of slurry generation in stone production (amount of generated stone slurry/amount of extracted stone)	Environmental Resource Preservation	Quantitative
Waste Processing (Treatment) Complexity Index	Measurement of complexity in the separation and extraction processes for usable and valuable materials	Socioeconomic	Qualitative
Toxicity Rate	Hazardous substances in slurry (toxicity level in terms of parts per million (ppm) concentration in collected slurry)	Environmental Socioeconomic	Quantitative
Upcycling Score	Comparison between a slurry-based product with a conventional product across various parameters categorised into environmental, social, resource preservation and economic aspects	Environmental Resource Preservation Socioeconomic	Quantitative

The Analytic Hierarchy Process (AHP), formalised by Saaty [58] and further discussed in [59,60], organises a decision problem into a hierarchy of goal, criteria and alternatives, derives priority weights from pairwise comparisons on a 1–9 verbal numerical scale and validates the resulting judgements through a Consistency Ratio (CR), whose acceptability threshold is 0.10. The present study adapts this procedure, as detailed below, to derive pairwise comparisons systematically from a preliminary rating step rather than through direct elicitation of each comparison. The six criteria in Figure 4 (data availability, ease of application, relevance, precision, complexity and standardisation) are compared pairwise and used to rank the 14 actionable indicators in Figure 5 as AHP alternatives. The complete pairwise-comparison matrix, the eigenvector, the priority weights and the consistency test are reported in the Supplementary Material and were computed with Super Decisions [61].

The pairwise judgements were not elicited directly on the 1–9 scale but derived from an intermediate 1-to-5 classification rubric. Each of the fourteen indicators was first scored by the research team, from 1 (low) to 5 (high), against each of the six criteria, using a written rubric anchored to data availability and applicability considerations drawn from the literature [2,4,15].

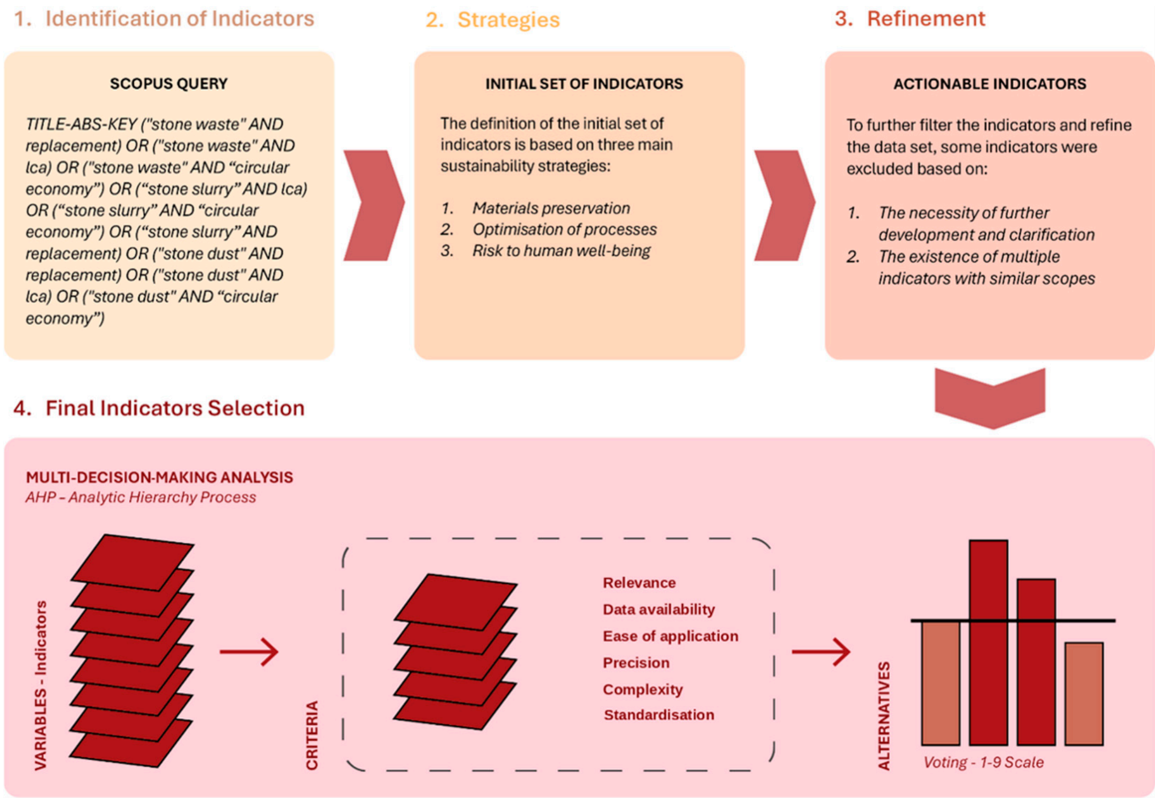

Figure 4. Methodology chart for the definition of circularity indicators applied to the stone sector.

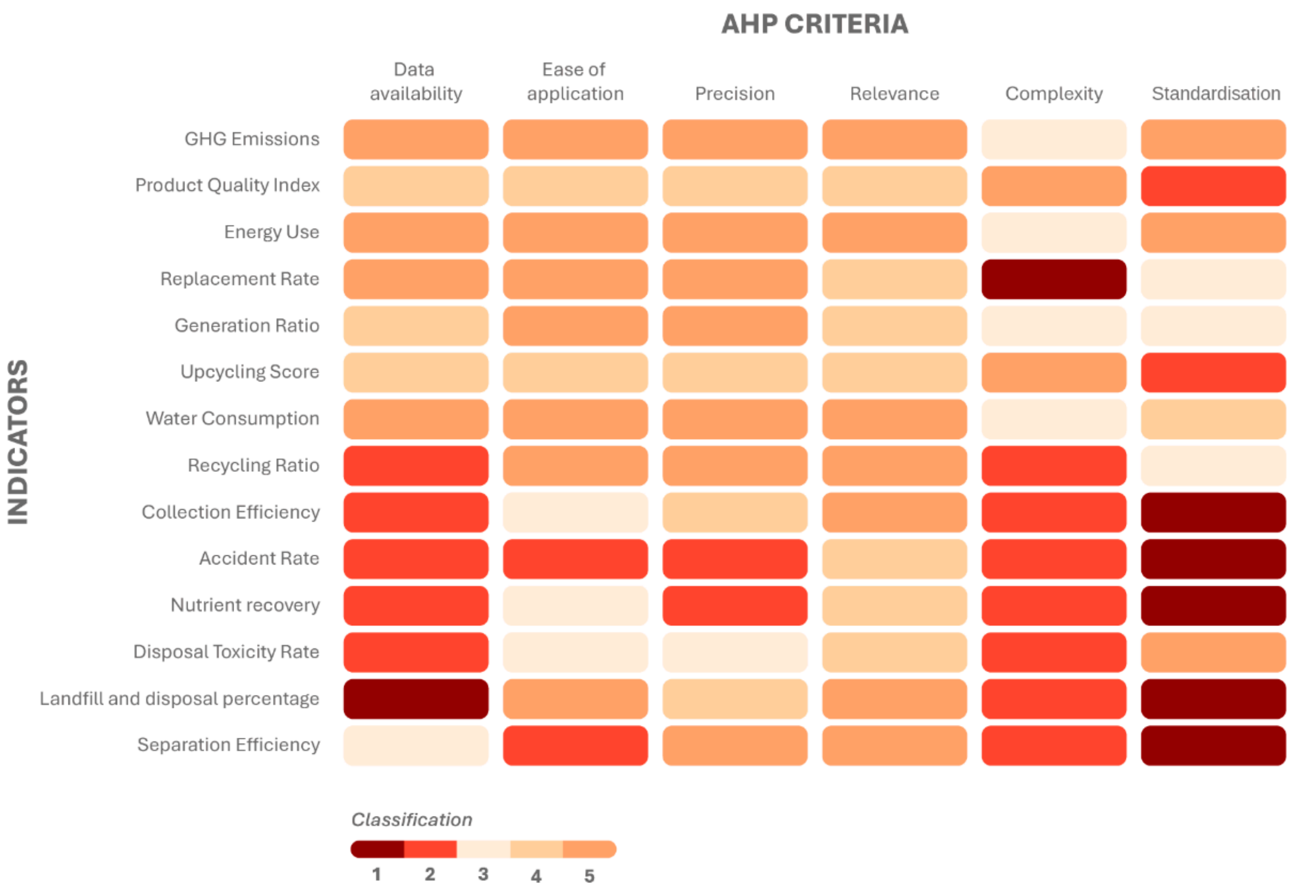

Figure 5. Refined stone waste indicators and respective criteria classification for AHP assessment.

For a given criterion, if two indicators i and j receive rubric scores s(i) and s(j), the corresponding Saaty pairwise value is obtained as $a(i,j) = |s(i) - s(j)| + 1$ when s(i) is greater than or equal to s(j) and as $a(i,j) = 1/(|s(i) - s(j)| + 1)$ when s(i) is less than s(j); indicators with equal rubric scores accordingly receive the neutral judgement $a(i,j) = 1$. This conversion was developed internally by the research team, through group discussion, as a structured device for reaching consistent judgements across the 84 indicator–criterion pairs required at this stage, rather than through unstructured, open-ended pairwise elicitation. A direct mathematical consequence of this deterministic construction is that every resulting pairwise value is an integer between 1 and 5 or its exact reciprocal; that is, intermediate or compromise values (e.g., 1.5, 6 and 7) cannot occur under this rule. The use of a capped, structured intensity scale of this kind is consistent with recent empirical findings that experts rarely use the upper end of Saaty's 1–9 scale in practice and that reduced or specialised intensity scales are a recognised feature of the AHP literature [62]. The complete derivation, including the formula and a worked example, is provided below and reproduced in full in the Supplementary Material.

For example, under the relevance criterion, GHG Emissions and Energy Use both received a rubric score of 5; applying the rule gives $a(i,j) = |5 - 5| + 1 = 1$, i.e., equal importance. By contrast, under the complexity criterion, Product Quality Index received a rubric score of 5 and Disposal Toxicity Rate received a score of 2; applying the rule gives $a(i,j) = |5 - 2| + 1 = 4$, meaning the Product Quality Index is judged as four times more important than Disposal Toxicity Rate on this criterion, with Disposal Toxicity Rate correspondingly receiving the reciprocal value 1/4.

This construction has two direct consequences for interpreting the results. First, the rule does not preserve Saaty's ratio-scale logic: a one-point rubric gap (e.g., scores 4 and 5) yields the same pairwise value as any other one-point gap (e.g., scores 1 and 2), although the latter represents a larger relative difference. The conversion is therefore a structured approximation suited to an initial, exploratory prioritisation rather than an equivalent restatement of Saaty's original scale. Second, because the resulting matrices are generated deterministically from a single score vector rather than through independent pairwise elicitation, the Consistency Ratio reported for each matrix (Supplementary Material) reflects the internal coherence of this construction rather than the reliability of independently elicited judgements, which is the basis on which Saaty's Random Index was calibrated.

The research team that carried out this scoring combines expertise in circular economy assessment, sustainability metrics and the natural stone sector. Each of the 84 indicator–criterion scores was assigned through open discussion among the research team, with the team proceeding to the next pair only once unanimous agreement on a score was reached. No averaging, voting or individual pre-scoring was used. Reaching agreement across all 84 pairs was practicable because the team is small and worked from a shared written rubric with defined score anchors, which narrowed the range of likely disagreement before discussion began. Most comparisons involved indicators with clearly distinct scores and were resolved quickly, while a smaller number of closer cases required longer discussion.

The choice to complete this first round within the team rather than through a broader expert panel is consistent with the exploratory scope of this work: in the absence of a validated CE indicator framework for the stone sector, the primary contribution here is to structure the problem and to demonstrate the feasibility of a sector-specific prioritisation, not to reach an industry-wide consensus. Consistency alone does not eliminate the risk of shared cognitive bias, nor does it capture the diversity of viewpoints between quarry operators, plant managers, LCA practitioners and policymakers. The framework is therefore presented as an initial, transparent proposal. The full pairwise-comparison matrices, eigenvectors and consistency tests for all seven AHP nodes (the criteria and the six indicator sets), together with a sensitivity analysis on the six criterion weights, are reported in the Supplementary Material.

Among the multi-criteria decision-making (MCDM) methods available for indicator prioritisation, AHP was preferred over TOPSIS [63] and PROMETHEE [64] for three reasons directly linked to the object of this study: the criteria used here are largely qualitative and intangible, a setting in which AHP is consistently reported to perform well [65]. TOPSIS and PROMETHEE both require an externally supplied weighting vector and quantitative performance data, neither of which is available for indicators still at the conceptual stage. Furthermore, AHP provides a built-in consistency test that acts as a quality gate on the pairwise comparisons, which TOPSIS and PROMETHEE do not.

The methodology for the definition of circularity indicators is defined in Figure 4. Given that the focus of this research is on the stone industry, the implementation scale is best considered at the micro level. This scale is particularly relevant for assessing the specific impacts and processes within individual organisations or facilities in the stone industry. The AHP assessment was performed using Super Decisions software V3.2.

In order to establish a consistent assessment within the 1–9 scale of AHP, the six criteria presented in Figure 4 (listed there in reference order) were categorised with a priority level derived from the pairwise comparisons: relevance, data availability, ease of application, precision and complexity and standardisation. These priorities were determined according to their definitions, the objectives of this study and established guidance for sustainability indicator development.

Relevance was prioritised first, as an indicator can only be considered fit for purpose once it is confirmed to align with the objectives of sustainability and circular economy and to capture pertinent material issues for both practical reality and policy making. This criterion acts as a precondition for the others: an indicator that is easy to apply, precise or standardised but disconnected from circularity principles has limited value, whereas an indicator anchored in circularity objectives retains value even where its data availability, ease of application or standardisation are still maturing. Consequently, this study places relevance at the forefront of the hierarchy, as without conceptual alignment with circularity goals, no amount of data availability, ease of application or precision can make an indicator meaningful.

Data availability was assigned the second priority, as the feasibility and reliability of any indicator depend fundamentally on the accessibility and quality of data. This criterion assesses whether the data required for the indicator are readily available, consistent and based on credible sources, such as industry reports, environmental databases and life-cycle inventories. In the stone industry, the lack of structured data on waste generation, reuse and recycling remains a primary barrier to circularity assessment. Previous studies have emphasised that data scarcity severely constrains the applicability and comparability of circular economy metrics, particularly in material- and process-intensive sectors [4,15,66]. Consequently, data availability was placed immediately after relevance, as without reliable data, even conceptually strong indicators cannot be validated or implemented in practice.

Ease of application was placed third, evaluating the practical effort required to implement the indicator, including the level of expertise, data collection and computational demand. Indicators that are overly complex or resource-intensive tend to be impractical for industrial adoption, even if they provide detailed insights [4,56]. This balance reflects the methodological consensus that successful indicators must be both applicable and meaningful [4,56].

In sequence, precision and complexity were treated as equally important secondary criteria. Precision measures whether an indicator is clearly defined, unambiguous and consistently measurable, thereby reducing subjective interpretation and enabling reliable longitudinal assessment. Complexity captures the degree to which an indicator integrates multiple sustainability dimensions—environmental, economic and social—or reflects system-level interdependencies. While both qualities are desirable, their importance is constrained in data-limited contexts, where excessive methodological sophistication may not yield proportionate decision-making benefits [5]. Thus, these criteria were positioned after relevance, data availability and ease of application, reflecting a pragmatic balance between analytical rigour and operational practicality.

Finally, standardisation assesses whether the indicator can be applied consistently across organisations, regions or timeframes, facilitating benchmarking and comparability. Although standardisation is essential for sectoral alignment and long-term monitoring, it typically evolves after initial adoption and testing of indicators [14]. Therefore, it was assigned the lowest priority in this study, acknowledging that harmonisation is a desirable future objective but not a current feasibility criterion.

The relative prioritisation of these criteria reflects both the theoretical underpinnings of circular economy measurement and the empirical realities of the stone industry. Following Saaty [58] and Vargas [59], expert judgement was used to construct the pairwise decision matrix, supported by literature-based reasoning to ensure consistency and transparency. This approach ensures that the AHP weighting is not arbitrary but grounded in a coherent rationale that integrates conceptual validity, data feasibility and sectoral applicability.

4. Results

4.1. Indicator Definition

From the preliminary identification of indicators, presented in Figure 3, and considering the strategies of the second step of the methodology, the number of indicators was further narrowed down, with some of them merged, as presented in Table 3. The initial set of indicators was defined, with explanations of what each measures, their category classification and measurement type.

The next refinement identifies the actionable indicators that are deemed relevant for stone purposes, filtered based on the two main aspects previously presented in Figure 4. With that analysis, 14 indicators are chosen, as presented in Figure 5. Each actionable indicator is evaluated according to the six criteria categories (data availability, ease of application, relevance, precision, complexity and standardisation) through the 1–9 voting system of AHP. In order to have coherent judgements, a classification of each indicator according to the criteria was defined, from 1 to 5, from low to high relevance, as further detailed in Figure 5.

The classification system is further detailed in the Supplementary Material, with a classification matrix for the criteria. Each indicator was classified, from 1 to 5, according to its relevance of each criterion. For instance, the indicator Landfill and Disposal Percentage was classified as 1 for data availability due to a lack of information on the post-use phases of slurry/stone waste materials. On the other hand, the indicator Replacement Ratio was deemed as 1 for complexity since it is the most narrowly focused indicator of the batch. Such an evaluation from 1 to 5 guided the AHP voting, from 1 to 9, when the indicators are compared with each other.

4.2. Final Indicators

The selection process of performance indicators for stone waste is presented in Figure 6. The graph represents the value of AHP ideals for each indicator, according to the performed voting. AHP produces a complete ranking rather than a threshold-based selection [58], so the definition of a working subset requires an explicit and reproducible criterion. In this study the criterion is that the retained indicators are those whose AHP-ideal score exceeds the arithmetic mean of the distribution. In Figure 6, this mean is 0.622 and separates cleanly into two groups: the seven top-ranked indicators (from Energy Use at 1.00 to Product Quality Index at 0.63) all score above 0.622, while the remaining seven (from Recycling Ratio at 0.57 to Accident Rate at 0.29) all score below it. The seven-indicator subset also covers all three CE strategies of Section 3 and, as shown in Figure 7, all CE requirements of Cayzer et al. [66] at least partially. The Consistency Ratios of the seven pairwise-comparison matrices underlying this ranking (the six criteria and the fourteen indicators under each criterion) range from 0.000 to 0.070, all well below the 0.10 acceptability threshold [58] (see Supplementary Material for exact values per matrix).

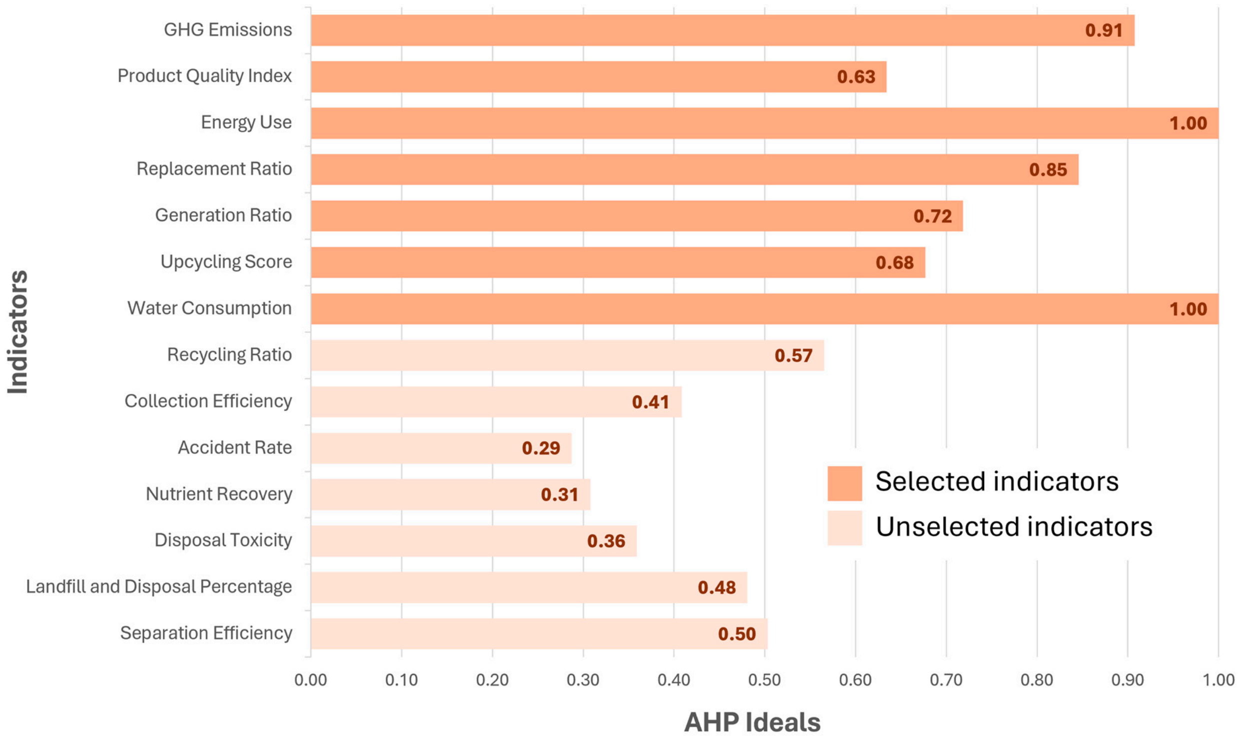

Figure 6. Final classification of indicators according to AHP criteria.

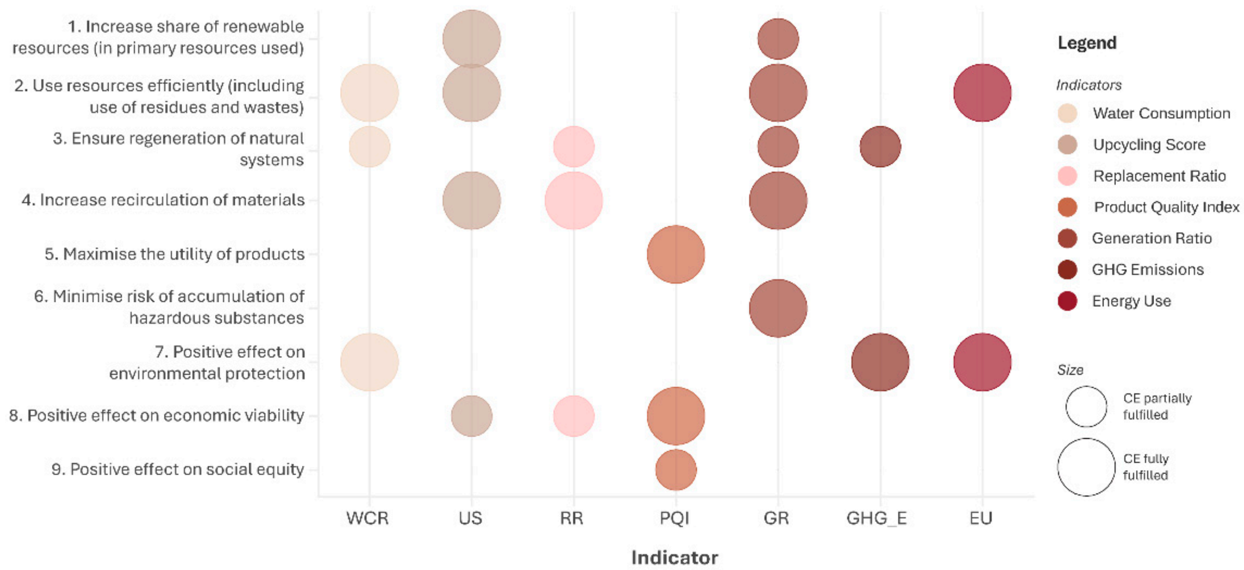

Figure 7. Tailored indicators for stone waste, according to fulfilment of CE requirements. Visualisation created with Flourish.

In order to further enhance the selection of the final indicators, a validation process was performed on CE requirements [67] and is shown in Figure 7. This proposition is to justify and analyse the selection of indicators. It is possible to observe that the central aspect assessed by the stone waste indicators is the CE requirement number 2, related to the effective use of materials. In addition, the gap of the three last requirements regarding broader aspects of sustainability, such as social equity, is also noted. However, the indicators proposed in this research present an opportunity to address it and evaluate the stone management holistically, as the final selection of indicators covers all of the requirements, even if partially.

Two safeguards were adopted to constrain the influence of subjective assumptions on the final indicator set: a written, literature-anchored classification rubric governing the 1-to-5 scores from which the pairwise comparisons were deterministically derived (Supplementary Material) and ex post validation of the resulting AHP judgements through the Consistency Ratio, which remained well below the 0.10 acceptability threshold for all seven pairwise-comparison matrices (Supplementary Material).

5. Discussion

Current circularity indicators often fail to address the specific needs of the stone sector. For instance, the heterogeneity in stone waste types (e.g., slurry, dust and solid waste) presents barriers in data collection. Several indicators, such as Material Circularity Indicator and Recycling Input Rate, rely on assumptions that may not be valid for stone waste. Such indicators often overlook the physical and chemical attributes of stone slurry, which influence recyclability and reuse potential. Assigning weights to indicators such as economic, environmental and social dimensions is particularly challenging in the sector. For instance, prioritising CO_2 emissions reduction over resource conservation may lead to skewed evaluations.

The complexity of using indicators in the stone sector stems from multiple factors, such as the variability in waste composition, due to the significant variation in mineral composition, making universal indicators challenging to apply. Moreover, the geographical and policy constraints, due to differences in regulations across regions, hinder the adoption of a standardised framework and resource allocation, as the industry often lacks investment in research and development for innovative waste management strategies.

The definition of seven final performance indicators potentially offers a more streamlined framework for assessing the sustainability of stone waste resources. However, data collection remains a critical challenge. Accurate and reliable data are vital for the effectiveness of the proposed evaluation. Indicators such as Greenhouse Gas Emissions, Energy Use, Replacement Ratio, and Water Consumption are not only crucial to the assessment but also benefit from ease of data collection. Conversely, collecting data for Upcycling Score and Product Quality Index indicators is more complex, mainly due to the scarcity of available and standardised waste-related data. In fact, the discussion on waste data and quantification remains limited in the literature [2], further underscoring such challenges. The development of further methodologies and frameworks to assess the stone sector's waste impact could incentivise an enhancement in data collection and supply chain monitoring. Unlike most previous CE frameworks that treat material flows generically, this study acknowledges that the waste profile of the stone industry is inherently heterogeneous, varying across lithologies such as marble, granite and limestone. Each stone type exhibits distinct mechanical and mineralogical properties that affect cutting losses, energy consumption and recyclability potential [1,2]. Therefore, future applications of the proposed indicators should integrate stone type-specific coefficients and life-cycle data to capture these variations. Similarly, regional policy environments exert a substantial influence on circularity outcomes. For example, the European Union's Circular Economy Action Plan [28] and Waste Framework Directive [68] strongly promote waste valorisation, while in major producing countries such as China, Turkey and India, regulatory frameworks still prioritise extraction efficiency and volume recovery. Embedding such policy dimensions into the indicator framework would enhance its global applicability and comparability.

In relation to the European Green Deal [69], the study proposes indicators, particularly those associated with Replacement Ratio, Energy Use and Greenhouse Gas Emissions, that can be directly aligned with the Circular Economy Action Plan. By incorporating these indicators into Environmental Product Declarations (EPDs) and extended producer responsibility schemes, enterprises can track compliance with EU sustainability targets and facilitate reporting within the EU Taxonomy for Sustainable Activities. At operational level, the four LCA-compatible indicators (Energy Use, Water Consumption, Greenhouse Gas Emissions and Replacement Ratio) can be populated with the same primary data collected for cradle-to-gate LCA and, therefore, reported alongside the environmental impact categories declared in Environmental Product Declarations for stone products [70]. At corporate level, the same four indicators can support the Corporate Sustainability Reporting Directive (CSRD). This connection establishes a tangible implementation pathway for the stone sector to align with European sustainability policies, providing actionable guidance for both policymakers and industry stakeholders.

In addition, the integration of such indicators into industry practice could enable more robust benchmarking and continuous improvement cycles. For instance, incorporating Replacement Ratio and Upcycling Score into procurement and environmental reporting could directly inform company strategy and policy design, supporting measurable progress towards CE goals. Furthermore, aligning these indicators with standard LCA methodologies provides a viable path for integration into existing environmental assessments, allowing for comparability across industries.

Compared to other mineral commodities, the stone sector is particularly exposed to supply chain constraints [71], but significant efforts have been made towards the improvement of current practices and the adoption of a sustainable approach [72,73]. Establishing a standardised methodology for evaluating waste repurposing thus contributes to both supply chain efficiency and sustainability.

The incorporation of circularity principles into stone slurry waste management serves as a fundamental tool for addressing environmental concerns, material conservation and socioeconomic benefits, ultimately benefitting multiple stakeholders, from sector leaders to policymakers. The motivation towards waste accountability and measurement could drive economic savings while reducing environmental impacts.

Policies promoting CE principles, such as extended producer responsibility (EPR) or waste valorisation incentives, could drive greater industry commitment to sustainable practices. Enhanced regulations across different jurisdictions would facilitate data collection and enable a more standardised approach to sustainability assessment within the stone sector. Future research could explore the role of policy interventions in shaping this industry's behaviour and improving the effectiveness of the proposed indicators. Finally, while the selection of seven key indicators provides a structured assessment, future studies should incorporate weighting methods to enable more robust comparisons.

The emphasis on feasibility and data reliability parallels the priorities identified in sectoral studies of construction material flows [14,15] and extends them by developing a structured AHP-based weighting specific to stone waste. By integrating expert elicitation, this work bridges the gap between conceptual CE frameworks [4] and operational industry applications, offering a transparent, reproducible model that can be adapted to other resource-intensive industries.

The seven-indicator subset is broadly consistent with three findings in the recent literature: the priority given to data availability criteria echoes the taxonomy of Saidani et al. [4], who identify data feasibility as the main constraint on the uptake of CE indicators in resource-intensive sectors; the high ranking of Greenhouse Gas Emissions and Energy Use aligns with Kristensen & Mosgaard [14], who report GHG and energy metrics as the most frequently retained indicators across micro-level CE frameworks; and the emphasis on Replacement Ratio parallels emerging marble-sector case studies where sludge substitution in cementitious and paint products is quantified as the primary circularity metric [74,75]. Unlike the composite Material Circularity Indicator of the Ellen MacArthur Foundation [11], the proposed framework deliberately does not aggregate indicators into a single score, since the heterogeneity of the stone waste stream would make such an aggregate difficult to interpret.

Furthermore, this framework directly addresses several long-recognised limitations of LCA when applied to circular systems. Traditional LCA struggles with end-of-life modelling, system boundary definition and accounting for secondary material loops, often underestimating the benefits of reuse and recycling [25]. The indicators identified in this study might complement LCA by introducing circularity-specific metrics that quantify material retention and recovery performance beyond conventional impact categories. Integrating these indicators with LCA enables a hybrid assessment approach, where environmental impacts are contextualised within material circularity performance. This provides a more comprehensive basis for evaluating the sustainability of stone products and waste management practices.

Overall, the proposed framework contributes to advancing both the theoretical understanding and practical assessment of circularity in the stone sector by identifying measurable and context-sensitive indicators that respond to the industry's specific challenges, such as data gaps, heterogeneity of waste streams and policy variability, while providing actionable insights for integrating circular principles into environmental assessment and regulatory reporting.

The seven indicators are not equally informative across all stone-sector contexts. In lithologies with high carbonate content, such as marble, the physical and chemical uniformity of the slurry supports high-confidence application of the Replacement Ratio and Product Quality Index, as evidenced by validated sludge-to-cement and sludge-to-paint case studies in the Italian and Iberian marble districts [74–76]. In silicate-based lithologies (granite), the same indicators remain applicable in principle but require lithology-specific reference data still scarce in the literature. In regions with mature CE regulatory frameworks such as the EU [28,68], all seven indicators can be embedded directly in reporting cycles. Where regulation still prioritises landfill diversion, the Replacement Ratio and Recycling Ratio are the most operationally meaningful metrics, whereas Upcycling Score and Product Quality Index remain longer-term monitoring objectives.

6. Conclusions

This study proposes an initial, sector-specific framework for evaluating circularity in the stone industry, with a particular focus on stone slurry. Existing CE indicators were systematically reviewed, refined through two suitability filters and prioritised through AHP, resulting in a set of seven candidate indicators—Energy Use, Water Consumption, Greenhouse Gas Emissions, Replacement Ratio, Generation Ratio, Upcycling Score and Product Quality Index—that span environmental, resource preservation and socioeconomic dimensions.

A key contribution of this research is the translation of CE principles into measurable and sector-specific metrics, addressing a gap explicitly identified in recent CE taxonomies.

In doing so, it reframes stone slurry from a linear waste by-product into a potential resource supporting reuse, reducing environmental impact and enabling new economic opportunities. It makes the refinement pipeline auditable, from the initial pool to the fourteen actionable indicators and the seven prioritised indicators, through explicit filters and a fully reported pairwise-comparison matrix. The selected indicators also provide an operational bridge between conceptual CE frameworks and existing reporting instruments such as EPDs and CSRD disclosures, which other resource-intensive sectors may adapt to their own waste streams.

Despite these advances, the study acknowledges challenges related to data collection, indicator standardisation and cross-regional applicability. Further empirical validation, especially through case studies and industrial partnerships, will be essential to refine these indicators and ensure their usability in real world contexts.

The framework should be interpreted as a working baseline rather than a validated tool. Its main limitations are the author-driven nature of the pairwise comparisons, reached by a single team through unanimous agreement rather than a broader or independently validated consensus process, the ratio-scale approximation used to derive pairwise values and the absence of an industrial-scale case study application. Future work will address the replication of the pairwise comparisons through a Delphi elicitation with quarry operators, plant managers, LCA practitioners and policymakers and the pilot application of the framework to a representative dimension-stone facility. A preliminary sensitivity analysis on the six criterion weights is already reported in the Supplementary Material. A fuller, expert-elicited sensitivity study, drawing on the broader Delphi panel described above, remains a priority for future work.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su18178980/s1, Table A.1: Voting from 1 to 9. Positive numbers indicates more relevance to the criteria in analysis, in comparison to another indicator. Negtive numbers indicate less relevance. Table A.2: Voting from 1 to 9. Positive numbers indicates more relevance to the criteria in analysis, in comparison to another indicator. Negtive numbers indicate less relevance. Table A.3: Voting from 1 to 9. Positive numbers indicates more relevance to the criteria in analysis, in comparison to another indicator. Negtive numbers indicate less relevance. Table A.4: Voting from 1 to 9. Positive numbers indicates more relevance to the criteria in analysis, in comparison to another indicator. Negtive numbers indicate less relevance. Table A.5: Voting from 1 to 9. Positive numbers indicates more relevance to the criteria in analysis, in comparison to another indicator. Negtive numbers indicate less relevance. Table A.6: Voting from 1 to 9. Positive numbers indicates more relevance to the criteria in analysis, in comparison to another indicator. Negtive numbers indicate less relevance. Table B.1: Criteria—Pairwise Comparison (Goal: Suitable KPI). Table B.2: Indicators—Pairwise Comparison (Criterion: Data Availability). Table B.3: Indicators—Pairwise Comparison (Criterion: Ease of application). Table B.4: Indicators—Pairwise Comparison (Criterion: Precision). Table B.5: Indicators—Pairwise Comparison (Criterion: Relevance. Table B.6: Indicators—Pairwise Comparison (Criterion: Complexity). Table B.7: Indicators—Pairwise Comparison (Criterion: Standardisation). Table B.8: Criterion and Composite Indicator Weights. Table B.9: Consistency Test Summary—All Matrices. Table B.10: Sensitivity Analysis—Criterion Weight vs. Global Indicator Ranking.

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