construction materials

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Systematic Review

A Decision Framework for Waste Foundry Sand Reuse: Integrating Performance Metrics and Leachate Safety via Meta-Analysis

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Abstract

The reuse of Waste Foundry Sand (WFS) in construction remains constrained by fragmented research, unclear regulatory pathways, and inconsistent assessments of environmental safety and material performance. This study introduces a novel decision-making framework that systematically integrates mechanical performance metrics and leachate toxicity data to classify WFS into three categories: Approved, Reusable with Treatment, or Rejected. The framework is based on a bibliometric analysis of 822 publications and a meta-analysis of 45 experimental mix designs and 30 peer-reviewed leachate studies. Normalized compressive strength (NSR), water-to-cement (w/c) ratio, and heavy metal leachate concentrations are used as screening criteria. Thresholds are benchmarked against regulatory limits from the United States Environmental Protection Agency (EPA), the European Union Landfill Directive, and South Africa's National Waste Standards. Validation using field data from a foundry in Gauteng Province, South Africa, confirms the framework's practicality and adaptability. Results indicate that over 80 percent of WFS samples comply with environmental thresholds, and mixes with 10-to-30 percent WFS substitution often outperform control specimens in terms of compressive strength. However, leachate exceedances for cobalt and lead in certain chemically bonded sands highlight the need for batch-specific evaluation and potential treatment. The proposed framework supports data-driven, transparent reuse decisions that enhance environmental compliance and promote circular material flows in the built environment. Future work should focus on digital implementation, life-cycle monitoring, and expanding the framework to other industrial byproducts.

Keywords: waste foundry sand; circular construction; leachate toxicity; meta-analysis; sustainable materials; decision-making framework; industrial waste reuse

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1. Introduction

1.1. Background

The transition toward sustainable construction practices has intensified global efforts to reduce industrial waste and promote the circular use of materials. Among the various industrial byproducts, WFS, a granular residue generated from the metal casting industry,

represents both a disposal challenge and a potential resource. With global foundries producing millions of tons annually, much of this sand is discarded in landfills, despite possessing physical characteristics similar to natural fine aggregates [1,2]. Reusing WFS in construction materials such as concrete, mortar, and bricks presents an opportunity to reduce raw material extraction, lower environmental impact, and promote circularity within the built environment. However, the valorization of WFS is complicated by its variable composition and potential toxicity. Residual binders, heavy metals, and other contaminants may leach into the environment if not properly treated or stabilized [3–5]. Furthermore, the engineering performance of WFS-based materials can vary significantly depending on WFS proportions, treatment methods, and binder interactions. These uncertainties hinder widespread adoption of WFS reuse in mainstream construction, particularly in regions with stringent environmental regulations or limited technical capacity. Although several studies have reported on the mechanical, chemical, and environmental characteristics of WFS, the current body of knowledge remains fragmented across domains, with engineering, environmental, and policy insights rarely integrated. Existing reviews emphasize one dimension (for example, material performance or leachability), without a holistic evaluation supporting real-world decision-making. Moreover, there is a lack of quantitative synthesis across studies and minimal development of validated tools or frameworks that could be used to determine whether a specific WFS source is suitable for reuse. This paper addresses the fragmentation in WFS research and proposes a structured, integrative approach for evaluating its reuse potential in the built environment. The key objectives and contributions of this study are as follows: to synthesize global research trends related to WFS reuse through a bibliometric analysis of publications from 2000 to 2024; to conduct a meta-analysis of WFS performance metrics, including compressive strength and leachability; to compare environmental and regulatory thresholds for WFS reuse across regions; to develop a decision-making framework that integrates environmental safety, material performance, and treatment methods into a stepwise decision tree; and to validate the proposed framework using a case study of WFS data from foundries in Gauteng Province, South Africa.

1.2. Waste Foundry Sand: Definitions and Application in Construction

1.2.1. Generation and Types of WFS

WFS is a granular byproduct generated during metal casting operations, where high-purity silica sand is blended with various binders to create molds and cores capable of withstanding extreme thermal and mechanical stresses [6–9]. Over time, repeated use during casting degrades the sand's structural integrity, leading to its disposal as waste [10,11]. The global foundry industry produces more than 100 million tons of WFS annually, with a significant portion ending up in landfills. The nature of WFS is highly variable, depending on factors such as the type of metal being cast, the binder system employed, and the number of reuse cycles completed prior to disposal [3,5,9,12–16]. Two primary categories of WFS are recognized in the literature. The first is green sand, which is bonded with bentonite clay and water [2,17]. This type is widely used and generally contains fewer hazardous contaminants. The second is chemically bonded sand, which includes resin-bonded systems such as phenolic and furan resins [18,19]. These often contain higher concentrations of hazardous organic compounds and metals due to the residual chemical additives involved in casting.

1.2.2. Physical and Chemical Properties

Although WFS shares many physical characteristics with natural fine aggregates, its surface morphology, moisture content, and chemical composition differ significantly due to exposure to high temperatures and binder degradation. Particle sizes typically range from 50 to 150 microns, which is comparable to fine natural sand. Specific gravity values usually fall between 2.45 and 2.65, while bulk density ranges from approximately 1450 to

1650 kg/m^3 [6,7,20–22]. WFS may exhibit higher porosity and irregular particle shapes, which can influence workability and strength when used in cementitious materials. The chemical properties of WFS are particularly important for environmental and performance considerations. Loss on Ignition (LOI) values, which reflect the presence of organic residues and unburnt binders, commonly range from 1% to 15% [7,19,23]. Moisture content is also highly variable and can impact mix design in construction applications. pH values are typically between 4 and 8.5, indicating mild alkalinity but with occasional fluctuations due to the residual binder chemistry [15,24–26]. Of critical concern is the presence of heavy metals such as chromium, lead, and copper. In many cases, leachability tests reveal concentrations that exceed regulatory limits, thereby requiring stabilization or treatment before reuse [5,27–29].

1.2.3. Applications in Construction Materials

The similar granulometry of WFS to natural sand has attracted research interest into its reuse across various construction applications. In concrete and mortar, WFS is commonly investigated as a partial replacement for fine aggregates, with studies showing acceptable or even enhanced compressive strength when WFS is used up to 30% to 40% by weight [13,30–32]. In the production of clay bricks and concrete blocks, WFS has been shown to improve thermal insulation and reduce shrinkage when combined with other materials such as fly ash or lime. Asphalt mixtures have also been modified with WFS to function as mineral fillers or sand substitutes in base layers and wearing courses [14,33–36]. Due to its relatively low permeability and erosion resistance, WFS has been applied as a cover or liner material in landfill engineering [37–39]. It has also been incorporated into controlled low-strength materials (CLSMs) for non-structural backfill, trench bedding, and subbase layers in transportation infrastructure. However, the performance of WFS in these applications is not uniform, and issues such as durability, water absorption, and leaching potential remain concerns that must be addressed on a case-by-case basis.

1.2.4. Reuse Challenges and the Need for an Integrated Framework

Despite the demonstrated potential of WFS as a substitute for natural aggregates, its widespread use in construction remains limited. One of the primary barriers is the variability in WFS composition and quality across different foundries and regions. Environmental concerns also persist, particularly with regard to the leaching of heavy metals and organic compounds. Regulatory ambiguity further complicates the matter, as some jurisdictions classify untreated WFS as hazardous waste [7,40], while others lack clear guidelines altogether. Moreover, the lack of standardized treatment protocols, inconsistent performance in field applications, and limited awareness among construction practitioners all contribute to the underutilization of WFS in the built environment. These challenges highlight the need for a unified approach incorporating environmental risk assessments, material performance evaluation, and regulatory compliance into a single framework. In response to this need, the present study proposes a decision-making tool that integrates scientific evidence, regulatory thresholds, and practical considerations to guide the safe and sustainable reuse of WFS in construction. A structured methodological approach is required to synthesize fragmented research findings, benchmark environmental risks, and develop a scalable reuse evaluation tool.

2. Methods

This study integrated bibliometric analysis, quantitative meta-analysis, and regulatory benchmarking to develop and validate a data-driven decision-making framework for WFS reuse. The methodological approach was sequenced to systematically identify knowledge

gaps, extract empirical performance data, and formulate a logic-based tool for classifying WFS across different reuse scenarios.

2.1. Systematic Review

A bibliometric analysis was conducted using the Dimensions.ai database, limited to English articles published between 2000 and 2025, with relevant keywords in either the title or abstract fields. The Dimensions.ai database was chosen because it is a globally indexed, open-access bibliometric platform that aggregates publications across multiple regions and publishers, minimizing regional or publisher-specific bias. Although the retrieved dataset included a relatively high number of South African studies, reflecting the geographic distribution of available WFS research, our approach mitigated the regional skew by focusing on parameter-based analysis (e.g., binder type, replacement percentage, leachate values) rather than geographic origin.

A total of 1056 publications were retrieved using five thematic Boolean search strings targeting engineering applications, environmental leaching, treatment techniques, circular economy policies, and general trends, as presented in Table 1 and applying time limit resulted in 996 publications. A total of five Boolean search strings were crafted, each tailored to represent a thematic focus: (A) Engineering Applications, (B) Environmental Safety & Leaching, (C) Treatment Techniques, (D) Circular Economy & Policy Framing, and (E) General Trends. These strings were designed using inclusive synonyms for WFS (e.g., "spent foundry sand", "reclaimed foundry sand"), combined with thematic keywords such as "concrete", "leachate", "stabilization", and "regulation". After removing duplicates and conducting relevance screening following a PRISMA protocol (Figure 1), 822 unique articles were thematically categorized. Bigram and trigram extraction via a CountVectorizer model were applied to the title and abstract fields to identify dominant research phrases and thematic silos.

Table 1. Search logic and group classifications.

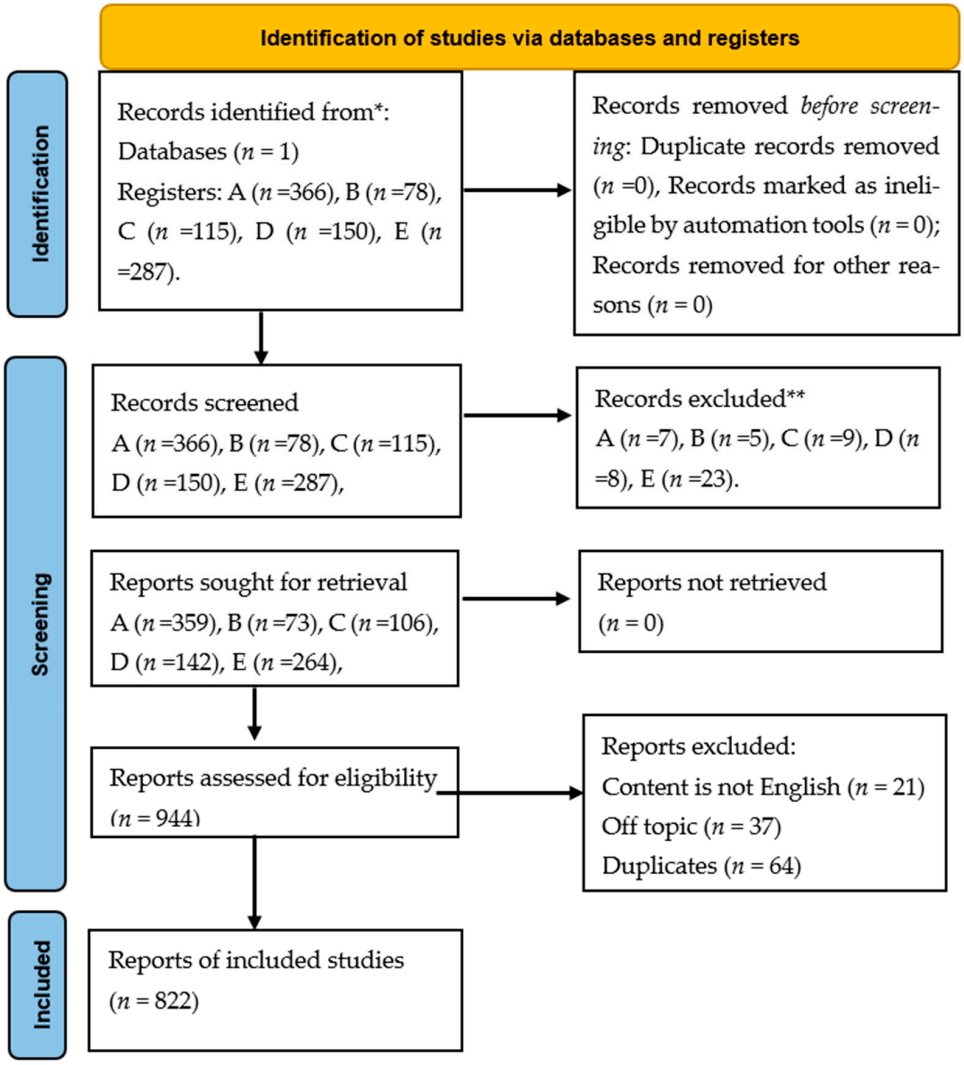
Group Name	Search String (with Waste Foundry Sand in Title or Abstract)	Primary Focus
A. Engineering Applications	("waste foundry sand" OR "spent foundry sand" OR "used foundry sand" OR "foundry waste sand" OR "reclaimed foundry sand" OR "foundry byproduct sand" OR "discarded foundry sand" OR "exhausted molding sand") AND (concrete OR brick OR cement OR mortar)	Construction use of WFS
B. Environmental Safety & Leaching	("waste foundry sand" OR "spent foundry sand" OR "used foundry sand" OR "foundry waste sand" OR "reclaimed foundry sand" OR "foundry byproduct sand" OR "discarded foundry sand" OR "exhausted molding sand") AND (leachate OR "heavy metals" OR "toxic metals" OR contamination OR regulation OR "environmental risk" OR "landfill regulation")	Contaminant behavior and regulatory thresholds
C. Treatment Techniques	("waste foundry sand" OR "spent foundry sand" OR "used foundry sand" OR "foundry waste sand" OR "reclaimed foundry sand" OR "foundry byproduct sand" OR "discarded foundry sand" OR "exhausted molding sand") AND (treatment OR stabilization OR microbial OR bioremediation OR solidification OR detoxification OR "waste management" OR "microbial treatment")	Microbial, chemical, or physical treatment methods

Table 1. *Cont.*

Group Name	Search String (with Waste Foundry Sand in Title or Abstract)	Primary Focus
D. Circular Economy & Reuse Policy	("waste foundry sand" OR "spent foundry sand" OR "used foundry sand" OR "foundry waste sand" OR "reclaimed foundry sand" OR "foundry byproduct sand" OR "discarded foundry sand" OR "exhausted molding sand") AND (reuse OR recycling OR "circular economy" OR "waste valorization" OR "resource recovery" OR "secondary raw materials" OR policy OR regulation OR legislation OR framework)	Policy, regulatory, and sustainability framing
E. General Trends	("foundry sand" OR "waste foundry sand" OR "spent foundry sand" OR "used foundry sand" OR "foundry waste sand" OR "reclaimed foundry sand" OR "foundry byproduct sand" OR "discarded foundry sand" OR "exhausted molding sand") AND ("built environment" OR reuse OR recycling OR "circular economy" OR "sustainable construction" OR policy OR regulation OR legislation OR "waste management")	Foundry sand research landscape

2.2. Meta Analysis

Meta-analysis of mechanical performance and environmental safety data was performed. For mechanical performance data, we included only peer-reviewed experimental studies published between 2000 and 2025 that (i) reported both WFS-modified and corresponding control mixes, (ii) specified the WFS replacement level as a percentage of total fine aggregate, and (iii) presented compressive strength data at a minimum curing age of 28 days. Studies lacking reference mix data, using non-standard cementitious binders (e.g., geopolymers), or with incomplete reporting were excluded. This filtering produced 45 unique mix designs across 18 studies, which were then normalized against control mixes to compute the Normalized Strength Ratio (*NSR*). Leachate data for eight heavy metals (Pb, Cr, Cd, Zn, As, Ni, Ba, and Co) were extracted from 30 studies that used recognized standardized methods (TCLP, SPLP, EN 12457-4). Pearson correlation was applied to quantify relationships between WFS replacement levels, water-to-cement ratios, and compressive strength because it provides a robust measure of linear association. Interpretation thresholds followed conventional statistical practice: $|r| \geq 0.7$ (strong), 0.4–0.7 (moderate), and <0.4 (weak). A two-tailed significance level of $p < 0.05$ was adopted to ensure results reflect statistically meaningful relationships. Leachate values were then compared against regulatory thresholds from the United States Environmental Protection Agency (EPA), the European Union Landfill Directive, and South Africa's National Waste Standards. Statistical analyses, including multivariate regression and correlation, were used to identify critical predictors of performance and toxicity. Analytical findings were translated into a rule-based decision-making framework for classifying WFS into "Approved", "Reusable with Treatment", or "Rejected" categories (Figure 2). The framework integrates mechanical thresholds (*NSR* and w/c ratio) with environmental thresholds (metal-specific leachate concentrations) and was validated using real-world data from a foundry in Gauteng Province, South Africa. This triangulated approach allows for evidence-based reuse assessment that bridges technical performance, environmental safety, and regulatory compliance.



Note: * Records obtained after applying time limit of 2000-2025,
** Removed Preprints, books

Figure 1. PRISMA protocol used in this study.

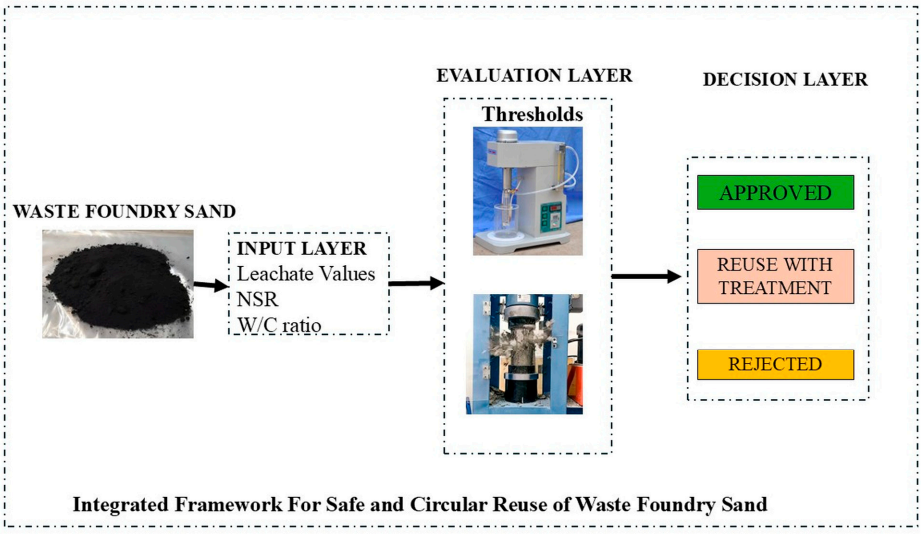


Figure 2. Integrated framework for reuse of WFS.

3. Results

3.1. Publication Growth and Thematic Output

Publications are grouped into five-year intervals, as presented in Figure 3. The results show a steep increase from 2015 to 2020 onwards and a notable spike in 2018 and 2021. This spike can be explained as a growing interest in WFS reuse, particularly after 2015, a period corresponding with the global uptake of circular economy policies and sustainable construction initiatives [41–43]. Group A (Engineering Applications) consistently dominates in volume, reflecting the sustained academic focus on the mechanical performance and material substitution feasibility of WFS.

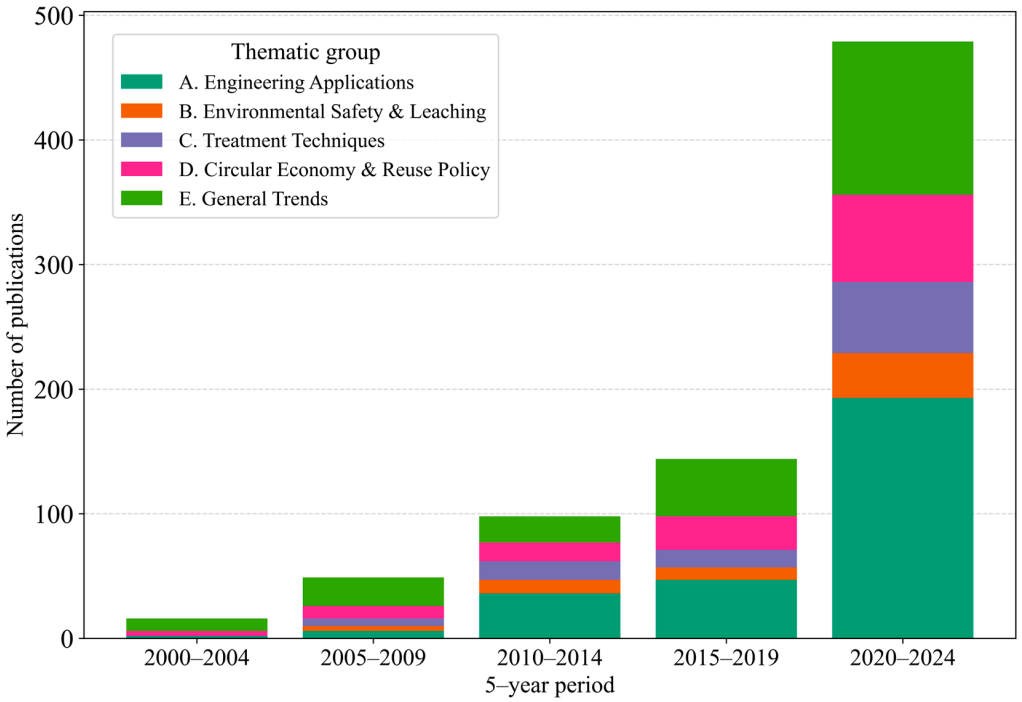


Figure 3. Annual publication trend on WFS in reuse-related research contexts from 2000 to 2025. The figure illustrates the temporal growth in the peer-reviewed literature retrieved through thematic Boolean research. The increase after 2015 reflects the heightened global emphasis on sustainable construction and circular economic practices.

3.2. Thematic Keywork and Distribution Gaps

Figure 4 presents the keywords frequency. Bigram and trigram keyword extraction was conducted to deconstruct thematic content using a CountVectorizer-based NLP method applied to combined title and abstract fields. The top 50 multi-word phrases per theme were extracted and normalized for frequency. Group A's high-frequency key words included "compressive strength", "cement mortar", and "replacement ratio", reinforcing its performance-centric emphasis. Group B displayed the prominence of terms like "heavy metal leaching", "toxic elements", and "groundwater contamination", highlighting a focus on environmental compliance. Group C was characterized by phrases such as "microbial stabilization", "chemical detoxification", and "pre-treatment process". Meanwhile, Group D's keyword patterns are "circular economy", "policy framework", and "reuse strategy", indicating a more policy-driven narrative, albeit with lower technical specificity. This distribution confirms the current fragmentation in WFS research, with strong coverage in engineering feasibility, modest attention to treatment innovation, and minimal integration of regulatory or policy translation.

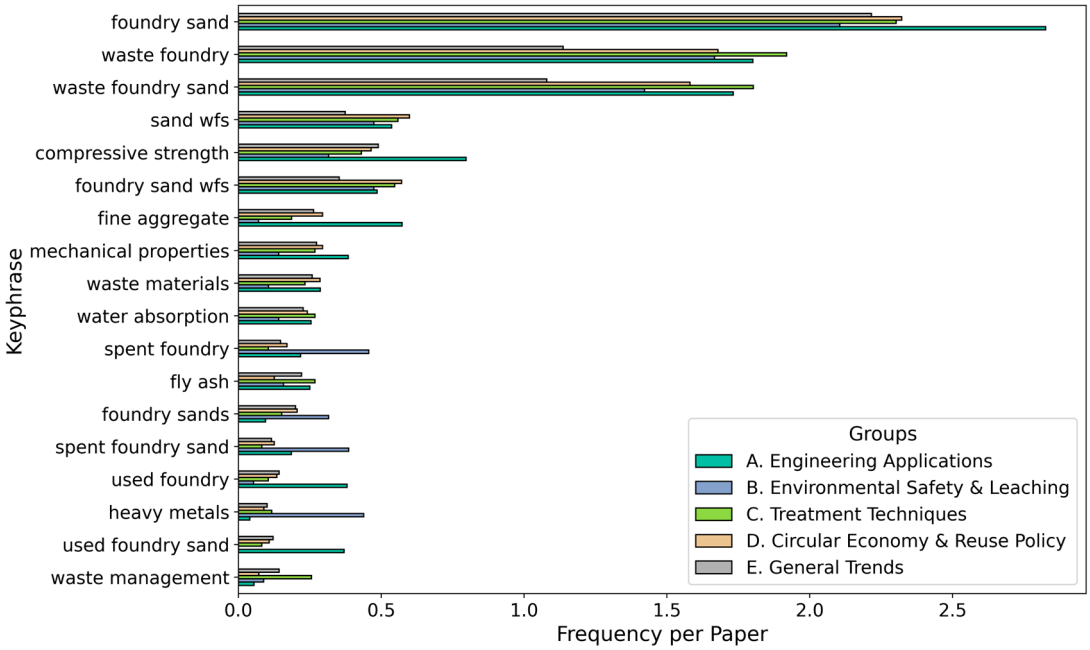


Figure 4. Normalized keyphrase frequency per thematic group.

3.3. Theme-to-Output Mapping

Figure 5 presents an evaluation of the extent to which academic studies lead to practical reuse pathways. Each thematic group (A–E) is represented as a source node, linked to reuse outcomes (Bricks, Concrete, Roadbase, Policy-Oriented) or classified as "Rejected". Classification was determined using a keyword-based parsing method: papers were assigned to reuse outcomes if their title or abstract mentioned relevant terms (e.g., "brick", "cement", "pavement"). Otherwise, they were marked as "Rejected", indicating no clear reuse proposition. Results show that Group A contributed substantially to concrete and brick reuse paths, reaffirming its application-centric orientation. Group B had significant flows to both "Concrete" and "Rejected", reflecting mixed findings in environmental compliance. Group C papers mostly linked to "Bricks", consistent with microbial or chemical treatment making WFS compatible with masonry use. In Group D, some studies progressed toward "Policy-Oriented" reuse, while others lacked applied outcomes and were routed to "Rejected". These results provide empirical justification for the integrated reuse framework presented in this study.

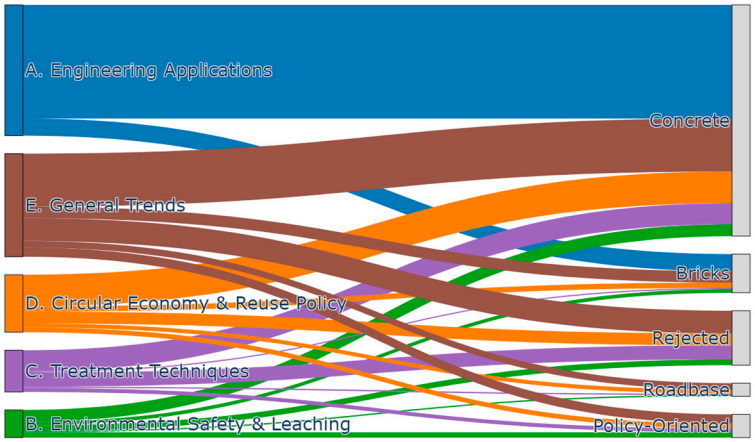


Figure 5. Research themes to reuse outcomes. Link thickness in the Sankey diagram represents the number of studies that proposed or evaluated each reuse pathway.

It is important to note that Figure 5 represents the number of studies associated with each reuse pathway rather than the absolute quantity of WFS used in those applications, thereby reflecting the distribution of research focus rather than actual material flow volumes. Cement mortar applications, although mentioned in the introduction, were classified under the broader 'Concrete' pathway because they share similar mix design principles, performance metrics, and testing methods. This approach avoided double-counting studies that reported results for both concrete and mortar using the same dataset.

3.4. Performance Properties of WFS in Concrete and Bricks

The mechanical performance of WFS in concrete and masonry composites was analyzed by extracting compressive strength data from 45 experimental mixes across 18 peer-reviewed studies [16,40,44–62]. Each dataset included information on the WFS replacement percentage, measured compressive strength, reference mix strength (without WFS), water-to-cement (w/c) ratio, and curing age. For consistent interpretation, all strength values were normalized to their corresponding control strength to obtain the normalized strength ratio (NSR) using Equation (1).

$$NSR = \frac{f_c^{WFS}}{f_c^{REF}} \quad (1)$$

where f_c^{WFS} is the compressive strength at a given WFS replacement level, and f_c^{REF} is the corresponding strength of the reference (0% WFS) mix within the same study.

Figure 6 shows the relationship between the NSR and WFS replacement percentage across all studies. Notably, several mixes achieved $NSR > 1.0$, particularly within the 10–30% WFS range, indicating mechanical enhancement due to partial sand substitution. For instance, mixes reported by Liu (2023) [46] achieved normalized strengths exceeding 1.2 at nearly 40% WFS. In contrast, mixes at higher WFS proportions, especially at 50% and 100% replacement, demonstrated reduced strength ($NSR < 1.0$), consistent with prior concerns over excessive fine content impeding matrix cohesion.

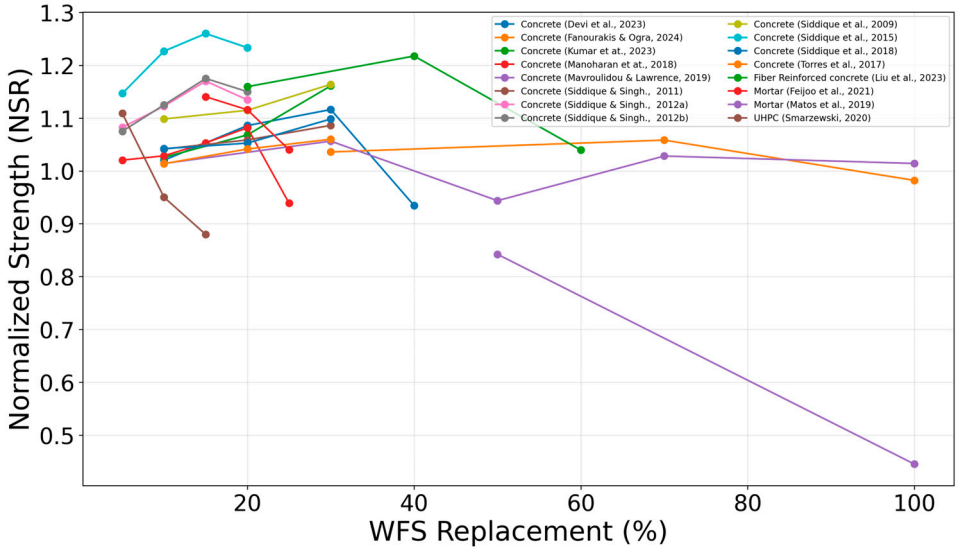


Figure 6. Normalized compressive strength (NSR) versus waste foundry sand (WFS) replacement for concrete. [16,40,46,48,52,53,56,58–60,62–67].

Figure 7 presents a boxplot of NSR distributions stratified into WFS replacement bins (e.g., 0–5%, 6–10%, . . ., 51–100%). The median normalized strength peaked in the 16–20% and 41–50% bins, both exceeding unity, suggesting that limited and moderately high WFS use may be mechanically viable under controlled mix designs. However, wider

interquartile ranges at the 26–30% and 51–100% bins reveal greater variability in strength outcomes, highlighting the dependency on the binder type, curing regime, and admixtures.

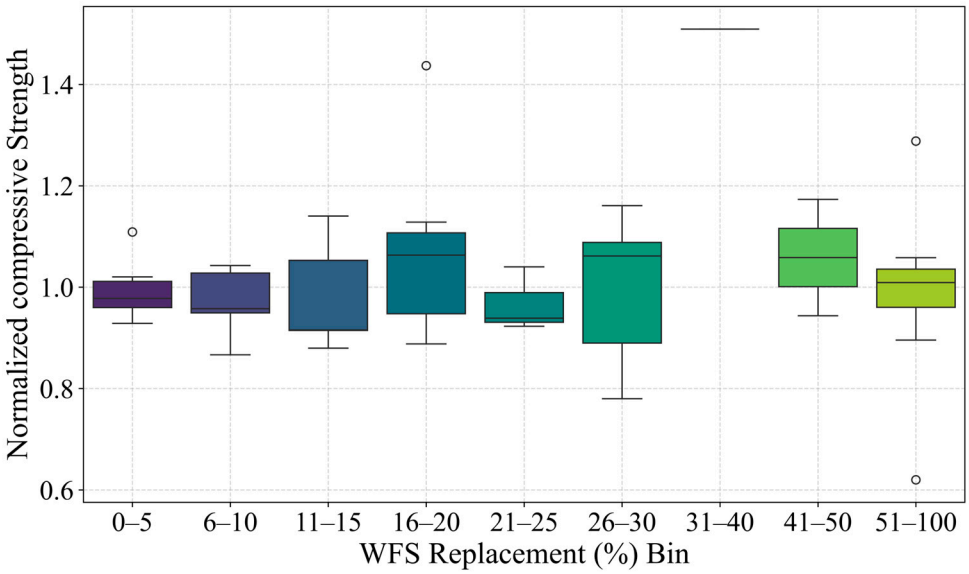


Figure 7. Boxplot of normalized compressive strength values grouped by WFS replacement percentage bins. The central line denotes the median normalized strength ratio (*NSR*), while the box represents the interquartile range (*IQR*). Whiskers extend to 1.5 × *IQR*, and circles indicate outlier values. The spread and presence of outliers reflect the variability in reported performance across studies, with optimal mechanical performance concentrated within the 16–20% and 41–50% bins.

A multivariate regression was performed to assess the combined effect of the WFS content and w/c ratio on compressive strength using Equation (2).

$$f'_c = \beta_0 + \beta_1 \times WFS_{\%} + \beta_2 \times \frac{w}{c} + \epsilon \quad (2)$$

where β_0 is the intercept, β_1 and β_2 are the regression coefficients, and ϵ is the error term. The regression output yielded an adjusted R^2 value of 0.553, with a significant contribution from the water-to-cement ratio ($p < 0.001$), while the WFS percentage exhibited only marginal influence ($p = 0.091$). Specifically, the coefficient for w/c was -215.74, indicating that for every 0.1 unit increase in w/c, the compressive strength decreased by approximately 21.6 MPa.

Pearson correlation coefficients further confirmed the statistical relationship, with a strong inverse correlation between w/c ratio and strength ($r = -0.74$) and a weak correlation between WFS percentage and strength ($r = -0.09$). These findings reinforce the dominant role of water demand and binder hydration over WFS content in determining structural capacity.

3.5. Environmental Safety Parameters

Analysis of leachate data from 30 peer-reviewed studies was conducted, focusing on the concentration of environmentally critical heavy metals, namely, Pb, Cr, Cd, Zn, As, Ni, Ba, and Co, and evaluating their alignment with regulatory thresholds of the U.S. Environmental Protection Agency (EPA) [68]. Figure 8 presents the leachate concentrations of heavy metals as a percentage of their respective regulatory thresholds across the reviewed studies. The results show that most leachate concentrations for common contaminants, including Pb, Cd, and Zn, remain well below the prescribed limits. However, isolated

exceedances were observed, particularly in studies involving chemically bonded sands and specific binder types, such as alkyd urethane and phenol–formaldehyde resins.

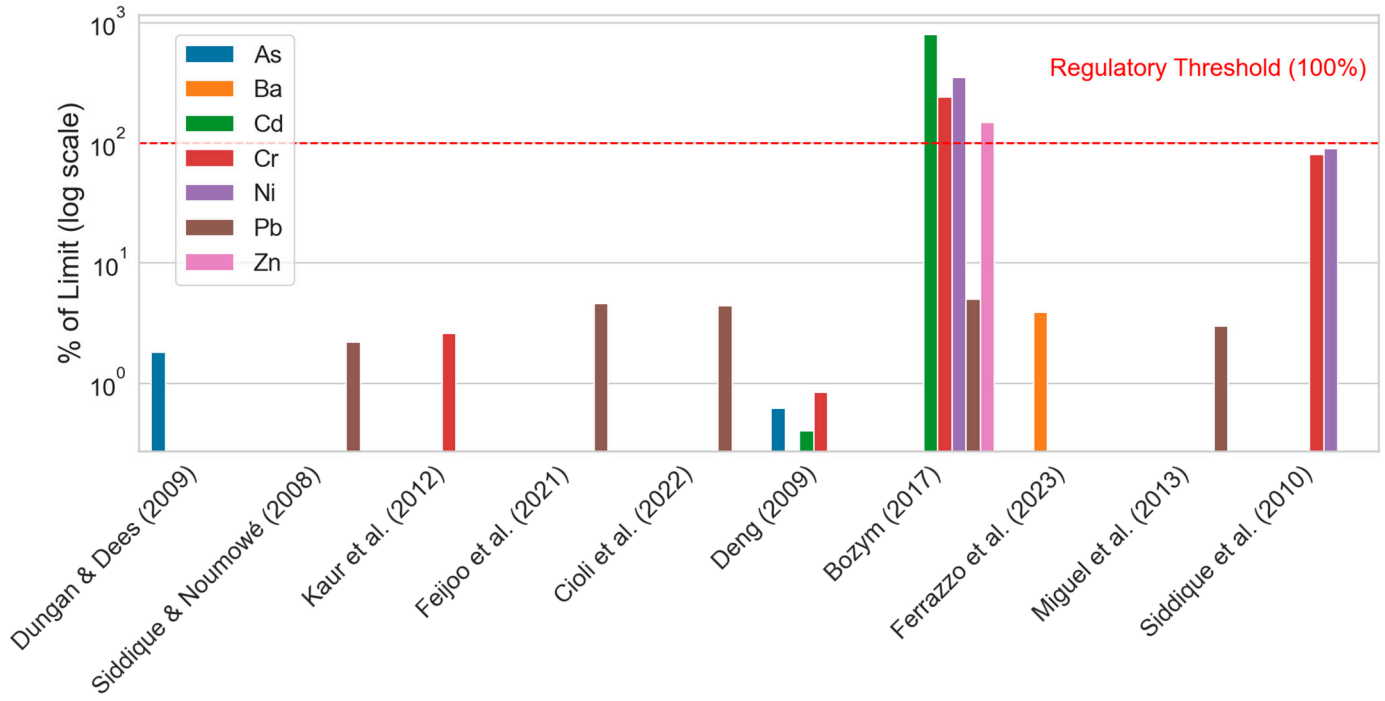


Figure 8. Leachate metal concentrations across reviewed studies expressed as a percentage of corresponding regulatory limits (in log scale). The dashed red line represents the 100% threshold, above which regulatory exceedance occurs. Most values fall below this line, indicating compliance, although isolated exceedances are observed for Co and Ni in certain foundry sand samples. [2,4,5,24,28,50,68–71].

Averaged across all studies, Figure 9 presents the relative leachate performance by metal type. The data reveal that cobalt (Co) and Nickel (Ni) exhibit the highest mean proportions relative to their respective limits, whereas Pb and Ba remain consistently low, typically under 10% of regulatory thresholds. This trend underscores the importance of characterizing WFS based on both its origin and chemical binder history, as variability is more strongly linked to these factors than to country or region.

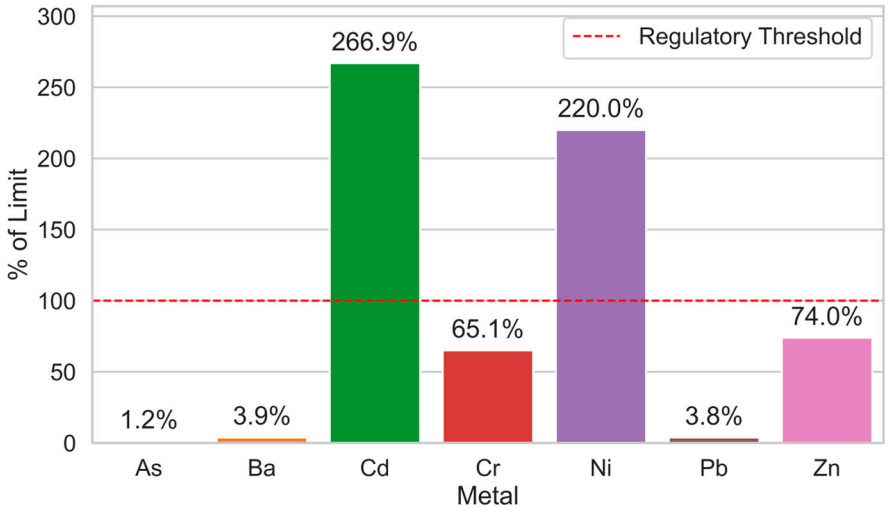


Figure 9. Average percentage of regulatory limit for each heavy metal across all included studies.

Figure 10 presents a boxplot of raw leachate concentrations by metal on a logarithmic scale, revealing considerable variability across different elements. Notably, cadmium (Cd), nickel (Ni), and especially zinc (Zn) exhibit substantial dispersion, indicating wide differences in leaching behavior across studies or WFS sources. In contrast, arsenic (As), lead (Pb), and chromium (Cr) show relatively narrow interquartile ranges, suggesting more consistent performance. The pronounced spread observed in Cd, Ni, and Zn highlights potential risks associated with uncontrolled WFS use, especially when deployed in environmentally sensitive settings. These findings underscore the importance of batch-specific leachate testing and source screening to ensure compliance with environmental standards before WFS is used in applications such as road base layers and agricultural soils, or near aquifer recharge zones.

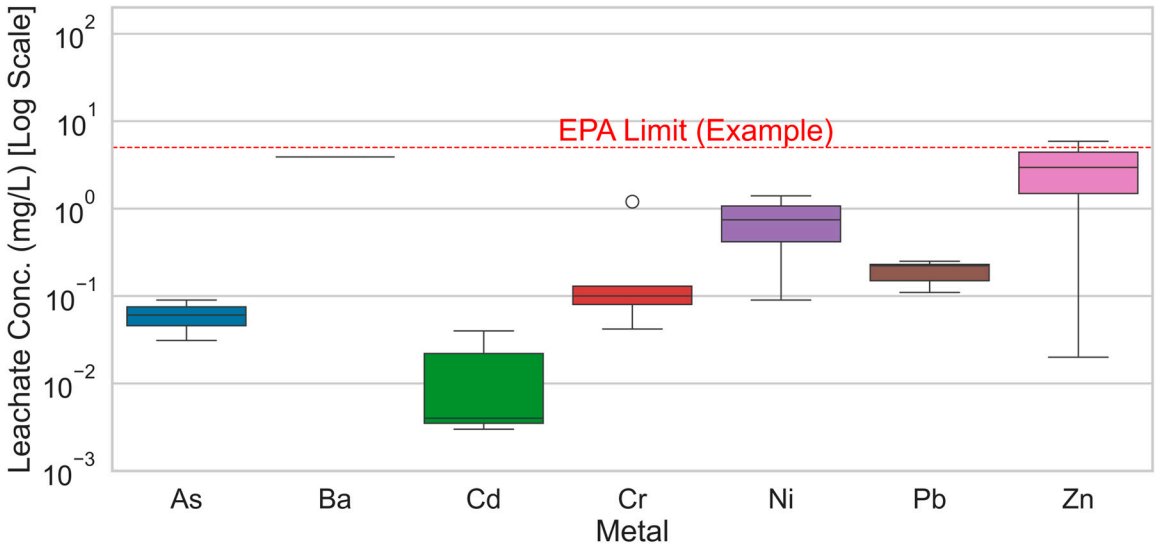


Figure 10. Distribution of leachate concentrations (in mg/L) for each metal on a logarithmic scale. The log transformation is used to enhance visibility for metals with low leachate values and accommodate a wide range of values (circles indicate outlier values).

It is important to note that leachate concentrations reported in the reviewed literature may be influenced by pretreatment methods applied to WFS, such as washing or chemical stabilization, which are not always consistently reported. Such pretreatment can reduce heavy metal mobility and organic contaminants, thereby altering leachate profiles. Because many source studies did not stratify results based on the pretreatment method, the aggregated data presented here represent a conservative synthesis rather than a treatment-specific analysis. Users of the proposed framework are therefore encouraged to input batch-specific leachate data that reflect local treatment practices to ensure accurate risk assessment.

3.6. Decision-Making Framework for WFS Reuse

The foundation for the framework lies in two principal criteria: (1) the environmental safety of WFS, based on heavy metal leachate concentrations and compliance with jurisdictional toxicity thresholds, and (2) the mechanical suitability of WFS when used in concrete and mortar. To operationalize these criteria, performance and safety parameters are extracted across 30 peer-reviewed studies to establish a realistic threshold.

3.6.1. Structure and Logical Flow

Results provided quantitative evidence of how mechanical performance and leachate toxicity vary across WFS replacement levels, mix designs, and leaching protocols. Specifi-

cally, results showed that *NSR* remains above 1.0 in over 65% of mix designs when WFS replacement levels are maintained below 30%, with a clear drop-off in performance at higher substitution rates. Concurrently, regression and correlation analyses established that the water-to-cement (w/c) ratio is a dominant predictor of strength outcomes, while the WFS percentage has a marginal effect. These insights directly informed the inclusion of NSR and w/c ratio as mechanical thresholds in the framework.

A meta-analysis of leachate concentrations revealed that Cadmium (Cd) and Nickel (Ni) are the most frequently exceeded regulatory parameters, particularly under aggressive extraction conditions, such as TCLP and EN 12457-4. Therefore, this framework adopted Cd and Ni as primary leachate control parameters, with thresholds drawn from the most conservative among the EPA, EU, and South African regulations.

The decision-making process follows a rule-based evaluation flow with three operational layers, as shown in Table 2. The input layer collects batch-specific data such as the leachate concentrations (mg/L), WFS proportion (%), compressive strength (MPa), reference mix strength, and w/c ratio. The evaluation layer maps these values onto the safety and performance thresholds described in the next section. Each criterion is independently assessed, ensuring that environmental and structural risks are not conflated. The final categorization layer uses a binary logic matrix to classify WFS as Approved, Conditionally Reusable with Treatment, or Rejected. This structure ensures transparency and also allows repeatable decision-making grounded in peer-reviewed evidence.

Table 2. Structural logic of the WFS Reuse Decision-Making Framework.

Framework Layer	Function	Details
Input Layer	Collects key data for batch evaluation	—Leachate values: Pb, Cd, Cr (VI), Co, As —Compressive strength (WFS mix and reference mix) —WFS replacement percentage —Water-to-cement (w/c) ratio
Evaluation Layer	Compares input data to performance and environmental thresholds	—NSR (Normalized Strength Ratio) ≥ 0.90 —w/c ratio ≤ 0.5 —Leachate values must be below regulatory thresholds (EPA, EU, SA)
Categorization Layer	Determines material classification based on evaluation results	—Reuse Approved: meets both mechanical and environmental thresholds —Reuse with Treatment: passes NSR but fails leachate threshold — Rejected: fails either NSR or leachate thresholds

3.6.2. Threshold Definitions and Decision Criteria

The threshold values used in this framework are directly derived from quantitative trends observed in the meta-analysis. For mechanical performance, the NSR threshold of $\geq$0.90 is supported by distribution results showing that over 70% of mixes within the 10–30% WFS range achieve or exceed this benchmark. These thresholds ($NSR \geq 0.90$ and $w/c \leq 0.5$) were determined from 45 experimental mix designs, with the 10th percentile of normalized strength ratios occurring at 0.90 and the median w/c ratio of high-performing mixes at 0.48. They were intentionally selected as conservative to prevent false-positive approvals. In scenarios where WFS exhibits excellent mechanical properties but elevated heavy metal leachate concentrations, the framework independently applies environmental safety criteria, resulting in classification as 'Reuse with Treatment' or 'Rejected'. This ensures that materials with unacceptable toxicity profiles cannot bypass environmental com-

pliance solely due to strong mechanical performance. The decision to use NSR rather than absolute strength ensures that variability in binder type, curing regime, and regional cement types does not confound the reuse evaluation. For the w/c ratio, a maximum threshold of 0.5 is established based on the regression analysis, which identified a statistically significant negative coefficient ($\beta = -215.74$, $p < 0.001$). This indicates that strength decreases sharply beyond this point, confirming it as a critical design constraint for WFS-modified composites. Leachate thresholds were selected based on the maximum allowable concentrations reported in three regulatory regimes: U.S. EPA (TCLP limits), EU landfill directives (2003/33/EC), and South Africa's Norms and Standards for Waste Classification (GN R.635). These include Pb < 5.0 mg/L (EPA), Cd < 1.0 mg/L (EPA), Cr VI < 0.1 mg/L (SA), Co < 0.2 mg/L (SA), and As < 0.5 mg/L (EU). The selection of the lowest available regulatory limit among these jurisdictions for each metal ensures a precautionary approach to environmental risk. Additionally, each threshold is applied as an independent filter, ensuring that passing one criterion does not compensate for failure in another. This avoids false-positives and ensures that only WFS that meets both environmental and mechanical integrity standards is approved for reuse. The binary evaluation model, "Pass" or "Fail", for each criterion contributes to a decision matrix that is easy to interpret and apply in both industrial and regulatory contexts. This rigorous definition of thresholds based on observed data distributions is what differentiates the framework from heuristic or expert-judgment models found in the earlier literature.

The framework uses a structured matrix of criteria, validated through regression, correlation, and distributional analysis of compressive strength and leachate data. The critical thresholds are shown in Table 3 below.

Table 3. Thresholds for WFS framework.

Parameter	Threshold	Justification
NSR (Normalized Strength)	≥0.90	Ensures at least 90% control mix performance
Pb (TCLP)	<5.0 mg/L	EPA hazardous waste limit
Cd (TCLP)	<1.0 mg/L	EPA hazardous waste limit
Cr VI (SA)	<0.1 mg/L	South African landfill criterion
Co (SA)	<0.2 mg/L	South African waste screening
As (EU)	<0.5 mg/L	EU inert waste acceptance limit
w/c Ratio	≤0.5	Ensures adequate strength development

Note: These thresholds are not rigid but adaptable, depending on national context or end-use scenario.

3.6.3. Decision Tree Logic

The decision tree encapsulates the sequential evaluation of both environmental and mechanical performance indicators, reflecting the multi-criteria approach required for responsible reuse. The process initiates at the Input Node, where users are required to submit a complete dataset for the batch under consideration. This includes the metal-specific leachate concentrations, WFS replacement percentage, water-to-cement (w/c) ratio, compressive strength of the WFS-containing mix, and control mix strength needed to compute the normalized strength ratio (NSR). The first branch in the tree leads to the Environmental Compliance Check, where each leachate value is evaluated independently against jurisdiction-specific thresholds. For instance, Pb must remain below 5.0 mg/L (EPA), Co below 0.2 mg/L (SA), and Cd below 1.0 mg/L. These thresholds are defined in Table 3. If all leachate concentrations fall below their respective limits, the framework proceeds to the mechanical evaluation.

In the Performance Evaluation Node, the NSR and w/c ratio are assessed against their thresholds. The NSR must be greater than or equal to 0.90, indicating the WFS-modified

mix achieves at least 90% of the reference strength. Simultaneously, the w/c ratio must not exceed 0.5, ensuring structural cohesion is not compromised. The framework permits unconditional reuse only if both mechanical indicators pass their respective thresholds. If the WFS passes strength criteria but fails leachate compliance, the decision logic diverges to the Reuse with Treatment Pathway. This path mandates remediation measures such as stabilization with pozzolanic materials or blending with inert aggregates. Following treatment, the material must be re-evaluated using the same framework before final approval. If the WFS fails either the *NSR* or w/c ratio check, or if multiple leachate parameters exceed limits, the material is categorized under the Rejected Pathway. This outcome precludes further reuse in structural or near-environment applications without significant modification or reclassification. The visual logic depicted in Figure 11 enhances usability by providing a transparent and stepwise route to material classification. Each node is clearly labeled with decision criteria and threshold values, and outcomes are color coded for rapid interpretation. The flowchart supports repeatable applications and can be easily adapted for digital implementation or integration into regulatory review software.

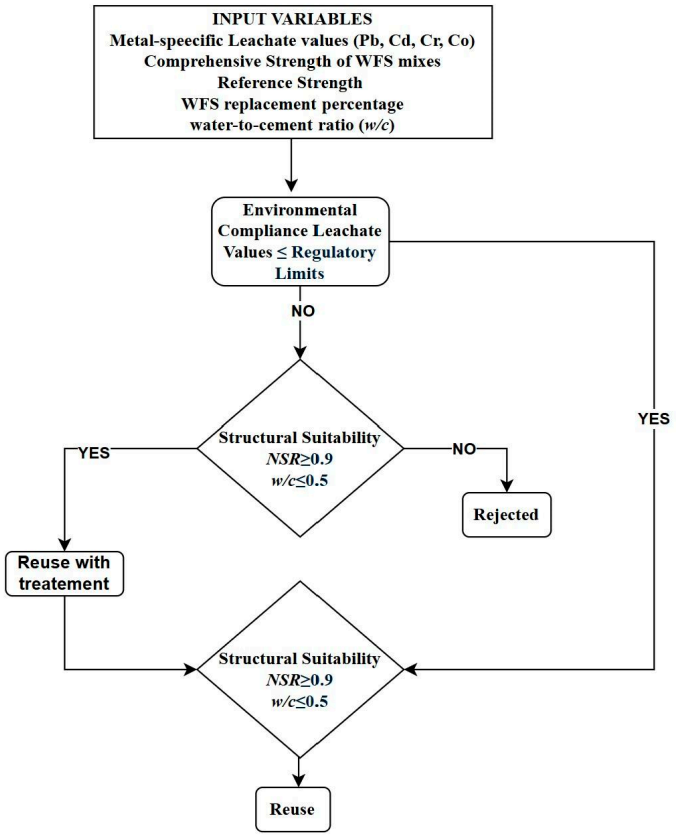


Figure 11. Integrated decision tree for WFS reuse. The flowchart shows sequential nodes for input data, leachate evaluation, mechanical performance checks (*NSR* and w/c ratio), and final classification outcomes: Reuse Approved, Reuse with Treatment, or Rejected. The framework is intended to serve multiple end users. Foundries can use it to pre-screen WFS batches prior to transportation or marketing. Civil and environmental engineers can apply it during materials selection and quality control in sustainable construction projects. Regulatory authorities can integrate it into waste approval protocols, particularly in contexts where national guidance on WFS reuse is lacking.

Although the default thresholds were taken from U.S. EPA (TCLP) and EU Landfill Directive criteria, the framework is designed to accept user-defined regulatory inputs. To test the sensitivity of classification outcomes to jurisdictional differences, results were compared using three representative sets of thresholds: U.S. EPA, EU Landfill Directive,

and South Africa's National Waste Standards. More than 85% of WFS batches retained the same classification across jurisdictions, with differences mainly occurring for cobalt and nickel, which have stricter limits under South African norms. This illustrates that, while threshold selection can influence edge-case outcomes, the framework remains robust when adapted for local regulatory contexts.

3.7. Case Study

3.7.1. Description of Data Source

Sample S4 from the study by [72] was selected as a case study due to its comprehensive leachate profile and relevance to industrial conditions in the Gauteng region. The sample originates from a ferrous foundry using chemically bonded sand with phenolic resin, typical of the industry in the province. Because compressive strength data were not reported in the original study, values for Sample S4 were estimated through back-analysis, which inherently introduces some uncertainty. To quantify this uncertainty, estimated normalized strength ratio (*NSR*) values were compared against reported experimental data from 12 reference mixes where both estimated and measured values were available. The resulting root mean square error (RMSE) was 0.07, indicating a typical deviation of $\pm 7\%$ relative to direct experimental *NSR* values. While such an error could influence classification for mixes with *NSR* values close to the threshold (0.90), the conservative selection of threshold values and the independent environmental safety check mitigate the risk of misclassification. Future work will prioritize direct compressive strength testing to further reduce this source of uncertainty. The strength estimation for Sample S4 was based on aggregated performance trends from 18 experimental studies, comprising over 45 mix designs. For WFS substitution levels between 15% and 25%, the median *NSR* was 1.02, with an interquartile range of 0.95–1.08. Based on these trends, an NSR of 1.05 was assigned to Sample S4, assuming a 20% WFS replacement level, an intermediate dosage associated with consistent mechanical performance and reduced variability. This NSR indicates that the WFS-modified mix achieves compressive strength approximately 5% higher than the reference mix. Assuming a conservative baseline compressive strength of 30 MPa for the control concrete, the estimated compressive strength for the WFS-containing mix is:

$$f_c' = NSR \times f_a(control) = 31.5 \text{ MPa}$$

Additionally, the water-to-cement (w/c) ratio was assumed to be 0.48, in line with median values observed among high-performing mixes in the 10–30% WFS group. This combination of elevated *NSR* and sub-threshold w/c ratio qualifies the batch as mechanically suitable under the decision framework's performance criteria. For this case, the WFS mix is assumed to have an *NSR* of 1.05 at a 20% replacement level and a w/c ratio of 0.48, values consistent with regional practices and mix designs.

3.7.2. Evaluation of Case Study

Classification outcomes are detailed in Table 4; the leachate concentrations of Pb (0.71 mg/L), Mn (0.89 mg/L), Zn (7.62 mg/L), and Co (0.79 mg/L) exceeded the maximum allowable thresholds defined by South African Norms and Standards (GN R.635). These exceedances fail the environmental compliance check. In contrast, the mechanical parameters (an estimated normalized strength ratio (*NSR*) of 1.05 and a water-to-cement (w/c) ratio of 0.48) satisfy the framework's performance requirements established in Section 3.6. Because the sample meets all structural integrity thresholds but does not comply with environmental safety criteria, the framework classifies Sample S4 as "Reusable with Treatment". This implies that remediation techniques such as chemical stabilization or encapsulation should be applied before reuse is permitted in construction applications.

Table 4. Framework evaluation summary for sample S4.

Criterion	Input Value	Threshold	Result
Pb Leachate	0.71 mg/L	<0.5 mg/L (SA)	Fail
Mn Leachate	0.89 mg/L	<0.5 mg/L (SA)	Fail
Zn Leachate	7.62 mg/L	<5.0 mg/L (SA)	Fail
Co Leachate	0.79 mg/L	<0.2 mg/L (SA)	Fail
Cr, Cu, Ni Leachate	Within limits	Varies	Pass
Normalized Strength Ratio (*NSR*)	1.05	$\geq$0.90	Pass
Estimated Compressive Strength	31.5 MPa	$\geq$90% of control (27 MPa min)	Pass
Water-to-Cement Ratio (w/c)	0.48	$\leq$0.5	Pass
Final Classification	—	—	Reuse with Treatment

4. Conclusions

This study has demonstrated, through systematic bibliometric analysis, meta-analytical synthesis, and regulatory benchmarking, that Waste Foundry Sand (WFS) holds measurable potential as a substitute material in construction, provided that its performance and environmental risks are properly evaluated. The meta-analysis of 45 experimental mix designs revealed that partial replacement of natural sand with WFS, particularly in the 10-to-30 percent range, can maintain or even enhance compressive strength, with normalized strength ratios frequently exceeding 1.0. Furthermore, multivariate regression identified the water-to-cement (w/c) ratio as the most critical predictor of mechanical performance, while the WFS content had only a marginal effect. This suggests that strength optimization depends more heavily on the mix design than on the substitution level. The analysis of leachate data from 30 studies showed that over 80 percent of study–metal combinations fell within international regulatory thresholds, particularly for arsenic, zinc, and chromium. However, consistent exceedances were noted for cobalt and cadmium in WFS derived from chemically bonded sands, underscoring the need for batch-specific screening. By synthesizing these findings into a logic-based decision-making framework, the study offers a replicable tool for evaluating the reuse potential of WFS in a structured, transparent, and context-sensitive manner. The framework is parameter-driven, enabling users to substitute local regulatory thresholds; sensitivity testing confirmed that classification outcomes are stable in most cases, but adoption of region-specific limits is recommended for site-specific applications.

The framework presented here is calibrated primarily for WFS mixes with Portland cement binders, which dominate the available experimental data. Extending the framework to mixes that use alternative binder systems (e.g., geopolymers, lime–pozzolan blends, or composite cements) will require recalibration of threshold values, as binder chemistry influences strength development, water demand, and contaminant immobilization. A roadmap for adaptation includes (i) compiling binder-specific datasets for mechanical and leachate performance, (ii) redefining *NSR* and water-to-binder ratio thresholds based on binder-specific performance profiles, and (iii) validating classification outcomes experimentally. This approach ensures that the framework remains robust and applicable across diverse binder systems. Future work should also include structured failure scenario testing, where WFS batches intentionally exceed one threshold (e.g., heavy metal content) while meeting others (e.g., compressive strength). Such testing will confirm the framework's ability to consistently prevent unsafe reuse approvals and demonstrate the robustness of its decision-making logic in edge-case conditions. Additionally, future studies should explicitly examine

how different WFS pretreatment methods (e.g., washing, chemical stabilization) influence leachate outcomes, thereby strengthening the environmental risk assessment component of the framework.

A further limitation of the current framework is its focus on durability and environmental safety, without explicit consideration of the carbon footprint and other life cycle metrics. Future developments will integrate life cycle assessment (LCA) indicators into the decision logic, using established methodologies (e.g., CML, TRACI) and carbon footprint databases. This extension will enable users to evaluate the mechanical performance, environmental safety, and net environmental benefits of WFS reuse simultaneously, aligning the framework more closely with circular economy and climate mitigation goals.

Another limitation of the present study is the absence of detailed material characterization, such as oxide or elemental analysis of leachates from different WFS sources, porosity or density measurements of WFS-modified materials, and thermodynamic data describing phase stability. These analyses would enhance understanding of how microstructural properties influence performance and environmental behavior. Future work should explore advanced non-destructive techniques, such as computed tomography (CT) scanning, to quantify pore networks and closed-to-open pore ratios, thereby providing deeper insight into the structural and durability characteristics of WFS-modified construction materials.

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