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Properties and development of industrial waste-based artificial aggregate for sustainable construction: a systematic review

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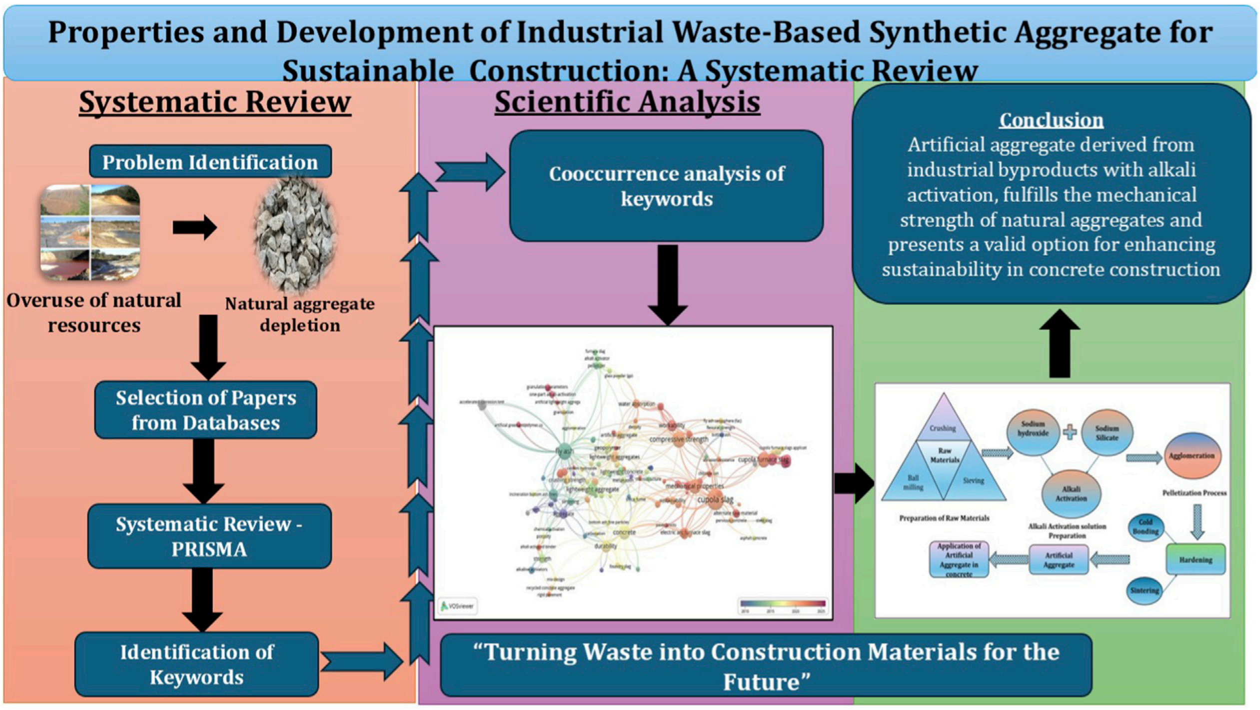
The rising global demand for construction materials and environmental concerns about natural resources depletion have driven research into byproduct-derived artificial aggregates as sustainable alternatives. This systematic review analyzes the manufacturing methods, properties, and performance of artificial aggregates produced from industrial byproducts, including Fly Ash(FA), Blast Furnace Slag (BFS), Steel slag (SS), Rice husk Ash (RHA), and Construction and Demolition Waste (CDW). Research indicates that artificial aggregates offer lightweight alternatives, exhibiting specific gravities 15%-30% lower than conventional aggregates. Aggregates made from industrial waste address waste management issues and reduce carbon footprints by 40%-50%. The review evaluates different manufacturing processes, such as cold bonding, sintering, and alkali activation, in producing sustainable artificial aggregates, and it also assesses their properties compared to natural aggregates. Production analysis shows cold bonding generates aggregates at ambient temperature, using 60%-85% less energy than sintering. The aggregates exhibit mechanical properties due to a 15%-30% reduction in porosity. Cold-bonded aggregates improve compressive strength and abrasion resistance by 20%-35% and 10%-25% respectively. This review, adhering to PRISMA guidelines, critically examines 100 studies indexed in Scopus from 2014 to 2024, offering a comparative analysis of both conventional and emerging artificial aggregate production methods. The findings highlight that performance and environmental benefits are highly context-dependent, with a particular emphasis on underexplored alkali-activated cupola slag–GGBS systems and their implications for durability, scalability, and practical implementation.

KEYWORDS
alkali activation, artificial aggregate, industrial byproducts, sustainable Construction, waste utilization

1 Introduction

The construction industry has been driving urbanization processes, infrastructure development, and economic growth in all parts of the world. During this rapid development phase, it has led to the overuse of natural resources, which has degraded the environment and produced waste (Gomathi and Sivakumar, 2014). Large quantities of solid waste are generated by the construction and demolition processes, which contribute to pollution and create problems related to waste management (Brandt, 2008).

Recycled concrete aggregates (RCA) and other cast-off materials are generally considered waste; although, research suggests that their recycling can mitigate environmental pollution (Hameed et al., 2025). Research on the use of these aggregates



GRAPHICAL ABSTRACT

in steel fiber reinforced concrete (SFRC) has been conducted regarding material properties and performance (Chen et al., 2025). Modern Construction techniques allow for the inclusion of recycled aggregates. Indeed, some constructions have been able to realize more than 20% replacement of natural aggregate. placement rates exceeding 20% (Farooq et al., 2023).Recent research indicates that the utilization of coarse and sand contributes to 1.8% of the total greenhouse gas emissions and impacts more than 1,000 species, out of which about 60% are threatened by the extraction of aggregates (de Bortoli, 2023).

Coarse aggregates are one of the vital constituents that contribute to the strength, dimensional stability, and resistance against water permeability in concrete (Ragavendra et al., 2021). The physical characteristics of these coarse aggregates, relating to their shape, size, specific gravities, and water absorption, affect the mechanical properties of concrete (Katiyar and Pal Singh, 2019; Yu et al., 2024). Natural aggregates, conventionally obtained from quarries by blasting and crushing, are widely used but create concerns about sustainability due to over-exploitation (Ragavendra et al., 2021). Recent advancements in material science have enabled the development of artificial aggregates, which are processed through the physical and chemical properties of available wastes (Kurzekar et al., 2024).

Artificial lightweight aggregates (ALCAs) derived from municipal solid waste incineration bottom ash (MSWIBA) or other industrial by-products typically exhibit a coarse surface texture, which enhances their adhesion to cement paste. Furthermore, these aggregates can immobilize heavy metals, thereby mitigating the leaching risk (Liu et al., 2022). They also contribute to the reduction of CO_2 emissions by decreasing the demand for natural aggregate extraction and waste management (Ibrahim and Atmaca, 2023; Jiang et al., 2020). Commonly used materials include fly ash, steel slag, ceramic waste, recycled concrete, and organic substances like coconut shell and oil palm shell (Islam et al., 2024; Liu et al., 2022; Shi et al., 2019). By replacing natural aggregates with recycled or artificial aggregates, we can mitigate environmental impact, conserve natural resources, and promote sustainable construction practices (Juenger et al., 2011; Vignesh and Abdul Rahim, 2024).

1.1 Knowledge gap

Despite the existence of numerous review studies on artificial aggregates derived from industrial by-products, these studies typically focus on specific waste materials or production techniques, offering primarily descriptive summaries. A comprehensive, performance-oriented comparison of different manufacturing processes remains limited. Alkali-activated artificial aggregates made from combined waste, such as cupola slag and GGBS, are rarely discussed in existing reviews and lack a thorough evaluation regarding mechanical performance, durability, and sustainability. This review addresses these gaps by offering a PRISMA-compliant, comparative analysis of artificial aggregate production methods, with a particular focus on underexplored alkali-activated cupola slag-GGBS systems. Furthermore, there has been insufficient emphasis on evaluating the practical implementation and technological readiness of these systems in comparison with traditional aggregate production techniques.

The review highlights, the growth of the construction industry has put a strain on natural resources and created major waste challenges. Using recycled and artificial aggregates, such as those derived from fly ash, steel slag, and recycled concrete, can help

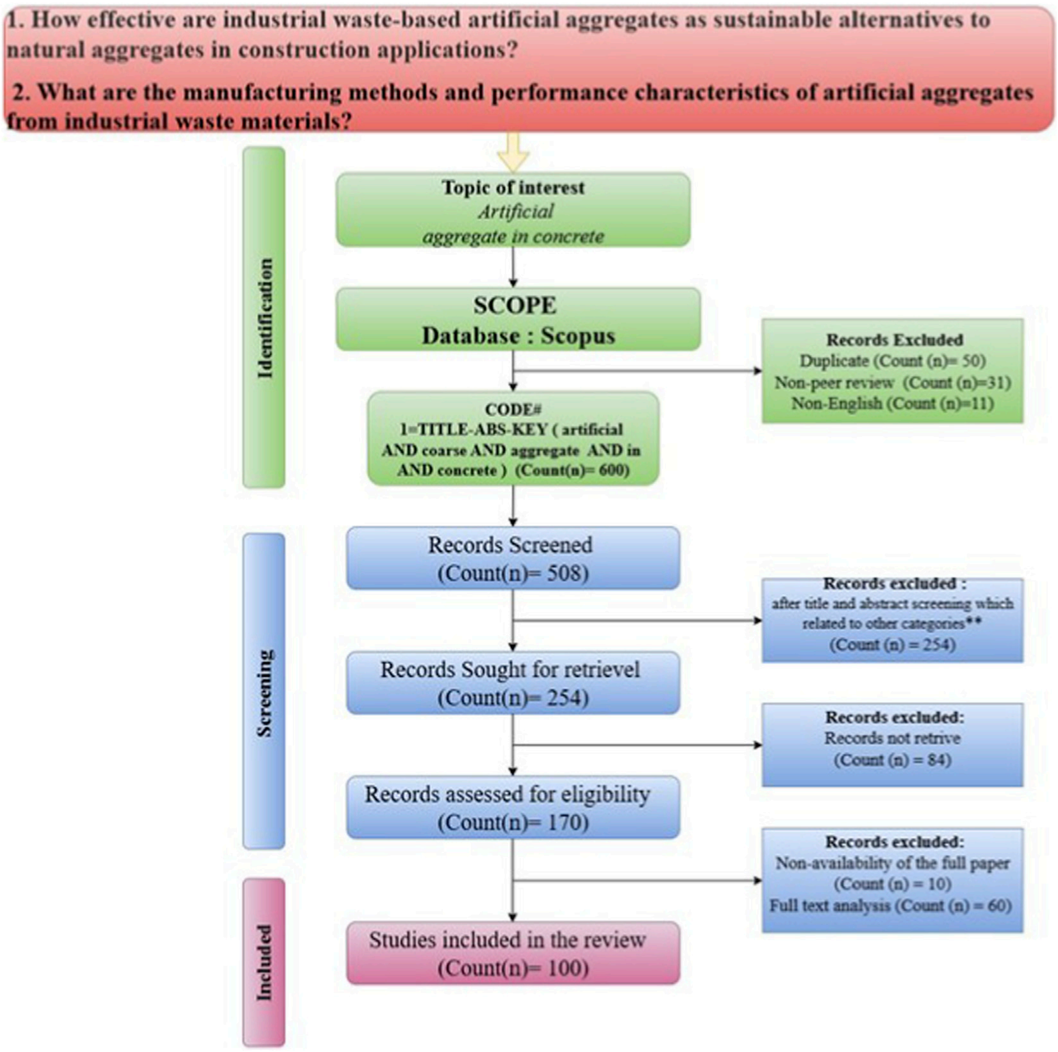


FIGURE 1
Prismastic representation of review.

minimize quarrying activities, lower CO_2 emissions, and transform waste into valuable materials. As the construction industry's sustainability challenges intensify, researchers are increasingly investigating artificial aggregates as viable alternatives to natural resources. This review examines their methodology (Section 2), Results (Section 3), literature review and types of aggregates (Section 4, Section 5), the utilization of waste materials (Section 6), physical properties (Section 7), mechanical properties (Section 8), and provides a conclusion, limitations, and future perspectives (Section 9, Section10, Section 11).

2 Methodology

Initially, 600 records on artificial coarse aggregate in concrete were retrieved from the Scopus database. Removing duplicates, non-peer-reviewed materials, and articles written in foreign languages reduced the number to 508 articles, evaluated based on their titles and abstracts. Further screening and acceptance assessments were conducted by rejecting topics irrelevant to the review and including unreadable articles in the systematic review. A sequence of steps illustrates an exhaustive procedure that assured the synthesis of only the most appropriate and reliable data for addressing the research questions.

The current study systematically reviewed the existing literature on industrial by-products, following the PRISMA or Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA). The PRISMA procedure recorded three primary stages for its assessment process: Identification, Screening, and Inclusion. Figure 1 shows the Prismatic representation of the Paper review.

2.1 Phase I -identification

A systematic search strategy was developed, initiated with the development of targeted research issues relating to the efficiency and production properties of artificial aggregates as sustainable alternatives to conventional aggregates. The Scopus database was

TABLE 1 Comparative assessment of review studies on artificial aggregate production methods and waste sources.

Study (year)	Waste/ Aggregate focus	Manufacturing methods covered	Databases used and period	Key metrics reported	Main conclusion	The gap addressed by the present review
Almadani et al. (2022)	Geopolymer artificial aggregates	Pelletization, sintering, cold bonding, and autoclaving	Scopus, up to 2022	Density (1.6–1.9), WA (7%–15%), strength (4–23 MPa)	Geopolymer AA is appropriate for use in lightweight concrete	Limited to geopolymer only, without incorporated steel or cupola slag, and it does not include an energy evaluation
Xu and Mo (2024)	CO_2-cured artificial aggregates from solid waste	Carbonation curing, granulation	Scopus, up to 2024	Density, strength, CO_2 sequestration	Carbonation improves strength and sequesters CO_2	Techniques are specially focused on carbonation curing, excluding alkali activation and cold bonding
Duan et al. (2025)	Cold-bonded AA from industrial waste	Cold bonding, pelletization	Scopus, 2000–2024	Physical/mech properties, sustainability	While CBAA is a sustainable option, there is a requirement to enhance its precursor	Cold bonding only; no sintering/alkali activation comparison
Qian et al. (2025)	Functionalized waste-derived AA	Granulation, functionalization	Scopus, up to 2024	Density, porosity, functionalization effects	Functional AA improves concrete performance	Narrow functionalization focus: there is no comparison of the manufacturing process
Stempkowska and Gawenda (2024)	Lightweight AA from CDW/plastics	Dynamic granulation, sintering/hydration	Scopus, up to 2024	Density 1.23 g/cm^3, porosity >30%	Dynamic granulation results in lightweight aggregates characterized by high-porosity	Granulation only; does not incorporate the alkali activation of slag or CDW.
Ibrahim and Atmaca (2023)	Cold-bonded and low-temperature sintered AA	Cold bonding, low-temp sintering	Scopus, up to 2023	Density (<2000 kg/m^3), WA, crushing strength	Cold bonding produces an effective lightweight AA	Limited scope; no comprehensive waste comparison or durability data
Our review	Fly ash, GGBS, steel/ cupola slag, RHA, CDW	Cold bonding, sintering, alkali activation	Scopus, 2014–2024	Physical (SG, WA, density), mechanical (crushing/impact), durability, energy/CO_2	Cold bonding + alkali activation yields 40%–60% CO_2 reduction; performance ranges and selection framework	Multi-waste, multi-method integrated synthesis with a quantitative environmental/ performance framework; unique cupola slag/GGBS focus

used due to its wide coverage of research into materials research. Concepts including “artificial coarse aggregate” and “concrete along with their combinations, were discovered, employing Boolean operators (“AND”, “OR”) to refine the analysis. Initially, 600 records were identified.

2.1.1 Literature search strategy

Scopus was chosen as the sole database for this systematic review because it extensively covers high-impact, peer-reviewed journals in fields such as Civil Engineering, Materials Science, and Sustainability research. In comparison to other databases, Scopus offers a wider range of indexing, advanced filtering capabilities, and standardized metadata, which are essential for achieving reproducibility in systematic reviews. Recent reviews in construction materials have effectively used Scopus as the only database, maintaining both coverage and quality. Utilizing a single, well-curated database helps to eliminate redundancy and ensures consistency in study selection while preserving methodological rigor. Table 1. Illustrate the Comparative assessment of review studies on artificial aggregate production methods and waste sources.

2.1.2 PICOS framework

To ensure clarity and reproducibility, the review protocol was developed using the PICOS framework (Population, Intervention, Comparator, Outcomes, and Study design), in line with the PRISMA 2020 guidelines.

Population (P): Concrete and mortar systems that utilize artificial or synthetic coarse aggregates derived from industrial by-products.

Intervention (I): Substituting natural coarse aggregates with those produced from industrial waste through methods such as sintering, alkali activation, cold bonding, autoclaving, and pelletization. These aggregates are made from materials like fly ash, GGBS, steel slag, rice husk ash, recycled concrete waste, and residues from municipal solid waste incineration.

Comparator (C): Traditional concrete that incorporates natural coarse aggregates or control mixes as reported in the selected studies.

Outcomes (O): Physical properties including specific gravity, density, and water absorption, mechanical properties such as compressive, split tensile, and flexural strength; durability indicators; and sustainability metrics, like energy consumption, CO_2 emissions reduction, and global warming potential.

Study Design (S): Peer-reviewed experimental studies, comparative analyses, performance analysis, durability and microstructural investigations, and life-cycle assessment studies published in indexed journals.

2.2 Phase II- performing the review

The screening procedure consisted of several stages to ensure a rigorous methodology. During the identification process, redundant data, unpublished research, and foreign journals were eliminated. Studies were subsequently evaluated based on their titles and abstracts for significance regarding artificial aggregates within concrete, with further eliminations made for unrelated topics. Records lacking retrievable text were also excluded, while the remaining articles underwent a comprehensive full-text review according to established inclusion and exclusion requirements, including quantitative data on efficiency and sufficient details about the methodology. A total of 100 studies were selected after these processes were completed. In summary, a total of 100 articles were selected based on specified inclusion and exclusion criteria.

2.3 Phase III- evaluation and presentation

The investigations were subjected to systematic description and data evaluation. Data were gathered and organized concerning aggregate forms, modes of production, properties, and performance measures. Synthesis was enhanced by visual aids, such as tables and diagrams of processes, while outcomes were compared concerning current study gaps and opportunities for the development of sustainable construction materials.

The method illustrated in the PRISMA flow diagram ensured that only relevant and high-quality materials were incorporated to meet the main goals of the review.

2.4 Research approach and data collection

The approach of systematic literature analysis was used in the review study to discuss recent developments associated with the generation of artificial aggregates by utilizing industrial wastes. A comprehensive search of academic databases was conducted to identify relevant peer-reviewed articles published in the last 10 years. Key search terms included "artificial aggregates", "industrial waste utilization", and "sustainable construction materials".

The selected papers were critically analysed to extract information on production methods, waste material utilization, physical and mechanical properties, and environmental impacts of artificial aggregates. Focus was given to studies involving fly ash, slag, recycled concrete, and other industrial byproducts.

2.5 Study Design

The research employs a systematic review approach, adhering to the PRISMA 2020 guidelines for systematic reviews and meta-analysis. The aim was to locate, screen, assess, and integrate existing studies on the use of industrial waste-derived artificial aggregates in sustainable construction.

2.6 Search strategy

The literature search was conducted in the Scopus database on [exact date, e.g., 15 January 2025]. The following Boolean search string was applied to titles, abstracts, and keywords: ("artificial aggregate" OR "synthetic aggregate" OR "manufactured aggregate") AND ("waste material" OR "industrial by-product" OR "slag" OR "fly ash" OR "GGBS" OR "cupola slag") AND ("cold bonding" OR "sintering" OR "alkali activation" OR "geopolymer" OR "pelletization" OR "autoclaving"). Only English-language articles published from 2014 to 2024 were included.

2.7 Data sources

The primary data source was the Scopus database. Additionally, reference lists from selected articles were reviewed to ensure a comprehensive collection of relevant studies.

2.8 Eligibility criteria

To maintain consistency and relevance in the synthesized evidence, eligibility criteria were established before the screening process, following the PRISMA 2020 guidelines. Figure 2. Illustrates the inclusion and exclusion criteria of articles.

2.9 Study selection process

The study selection involved three phases: Identification, screening, and inclusion. After eliminating duplicates and irrelevant records, titles and abstracts were reviewed for relevance. Full-text articles were then evaluated against the inclusion criteria.

The selection process is depicted using the PRISMA 2020 flow diagram (Figure 1).

2.10 Data extraction

Data extracted from each eligible study included: type of waste material, aggregate manufacturing method, curing technique, physical properties, mechanical properties, durability indicators, and sustainability metrics.

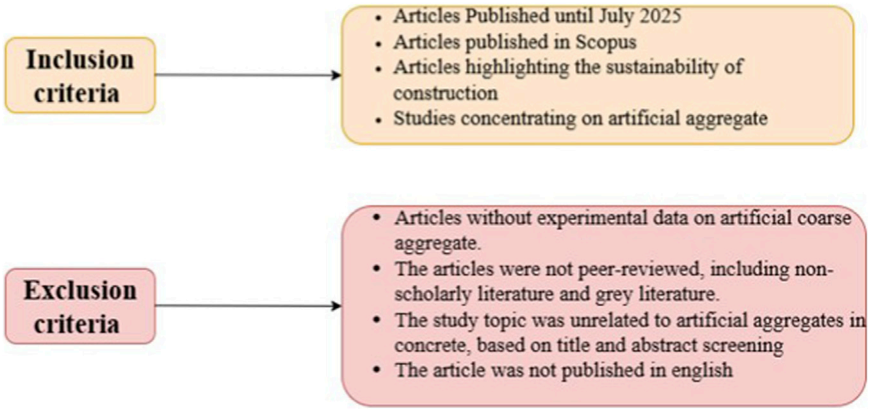


FIGURE 2
Inclusion and exclusion criteria.

2.11 Data synthesis

The final collection of studies was organized according to (i) the method of aggregate production, which includes sintering, cold bonding, autoclaving, alkali activation, and pelletization, (ii) the type of waste materials utilized (GGBS, cupola slag, steel slag, fly ash, and mixed wastes). Tables and figures were employed to summarize trends, ranges, and performance comparisons.

2.12 Risk of bias assessment

Potential bias sources were assessed qualitatively. Bias could stem from the choice of database (reliance on a single database), publication bias favoring positive results, and differences in experimental protocols across studies. The limitations were considered when interpreting the synthesized outcomes.

3 Results

3.1 Year-wise publications

Research and industrial development on artificial aggregates have grown rapidly over the past 10-15 years, driven by sustainability goals and the need to conserve natural resources. Initial (Islam et al., 2024; Ye et al., 2025).Studies have primarily focused on aggregates derived from fly ash. Still, subsequent research has expanded to include steel slag, recycled concrete, and municipal solid waste, employing increasingly advanced techniques such as alkali activation. Figure 3 shows the overview of the article.

Since 2020, publications have risen sharply, exploring new waste combinations, refining production processes, and assessing mechanical, durability, and microstructural properties in greater depth. Recent work also emphasizes environmental impact assessments and life cycle analyses, while market forecasts predict that the global artificial aggregates sector will reach US$56.19 billion by 2030. These developments underscore the increasing importance of artificial aggregates in sustainable construction and global infrastructure development (Stempkowska and Gawenda, 2024; Ye et al., 2025). Figure 4 shows the year-wise publication of artificial aggregates in concrete.

3.2 Country–wise publications

Figure 5 illustrates the worldwide distribution of research articles about artificial aggregate materials. Showing a concentrated research focus headed by India and China, where each country accounts for 28% of the publications, indicating their substantial construction needs and emphasis on sustainable material advancement. The remaining research output is distributed among Iraq, the United States, and Saudi Arabia (7%), Malaysia and Pakistan (6%), and other countries, less than 5%. The international community's recognition of artificial aggregates highlights their importance in sustainable constructions. Developing nations are spearheading innovation initiatives to accelerate infrastructure developments, reduce environmental effects, and utilize waste materials such as flyash and construction waste (Almadani et al., 2022).

3.3 Analysing key journals

According to SCOPUS statistics, the top 10 core publications are ranked by building materials publications, with title, publishers, and 2025 SCOPUS cite score listed. High SCOPUS citation scores indicate greater citation impact per work. Frequently cited journals with many references rank higher. Elsevier and Springer Nature are the leading publishers of significant research. "Journal of Cleaner Production," though not in the top 10, achieves higher citation rates (19.3). Top-ranked journals publish quality papers with high citation rates. Higher citations and frequently referenced articles lead to increased SCOPUS cite scores (Table 2). These periodicals drive construction materials research, as defined by their volume and impact. Systematic examination reporting follows this methodology.

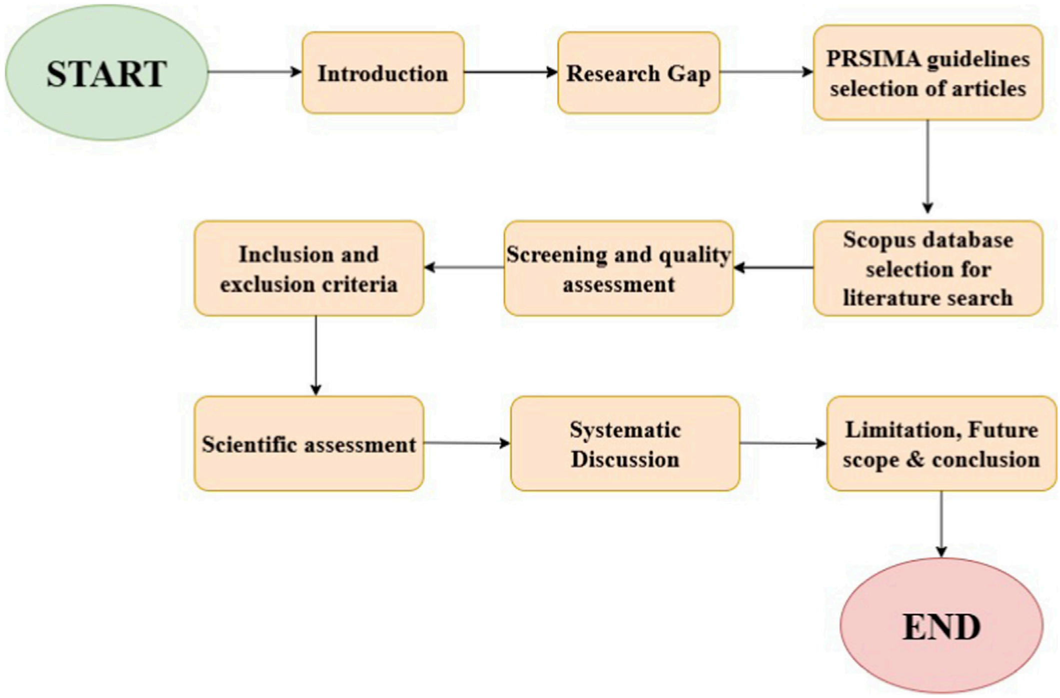


FIGURE 3
Overview of the review article.

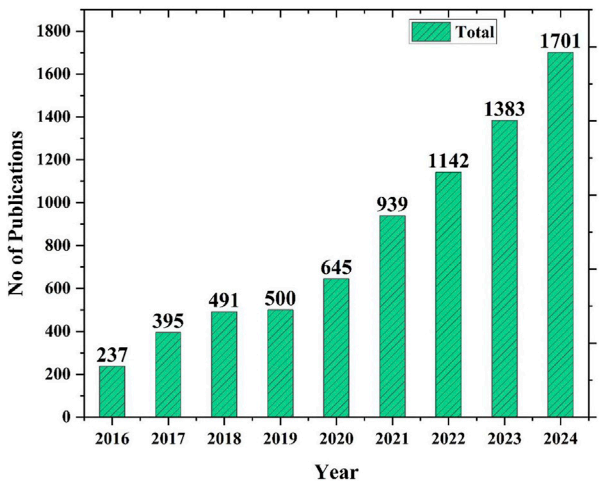


FIGURE 4
Year-wise publication.

A Comprehensive review of artificial coarse aggregate in concrete revealed 600 records, which were carefully examined to identify 100 high-quality studies. Publications have increased significantly since 2020, focusing on mechanical performance, sustainability, and life cycle effects. India and China are the world's leading contributors, highlighting their crucial position in advancing sustainable construction innovations.

4 Literature review

4.1 Manufacturing methods for artificial aggregates

The research provides three artificial aggregates manufacturing processes for various uses.

4.1.1 Overview of conventional process

Moulding is used in laboratories to examine pore-filling agent effects, but not for mass production. Crushing solidified paste produces sharp-edged aggregates for applications in industry with less particle homogeneity control. Industrial waste, binder, and water are hand-shaped into spherical pellets and air-dried and cured under various conditions, although this procedure is not scalable for industrial usage. Figure 6 shows the artificial aggregate production.

4.1.2 Pelletization process

Pelletization is a widely adopted process for converting fine powder (fly ash, quarry dust, slag) into spherical, free-flowing pellets with enhanced strength (Geetha and Ramamurthy, 2010). The process involves feeding dry materials into a pelletizer drum or disc, spraying water to form agglomerates, and adjusting drum speed (40 rpm), angle (25^0-45^0), and moisture content to ensure uniform size and strength (Harikrishnan and Ramamurthy, 2006; Khan Baykal et al., 2000).Pelletization is a highly sustainable process

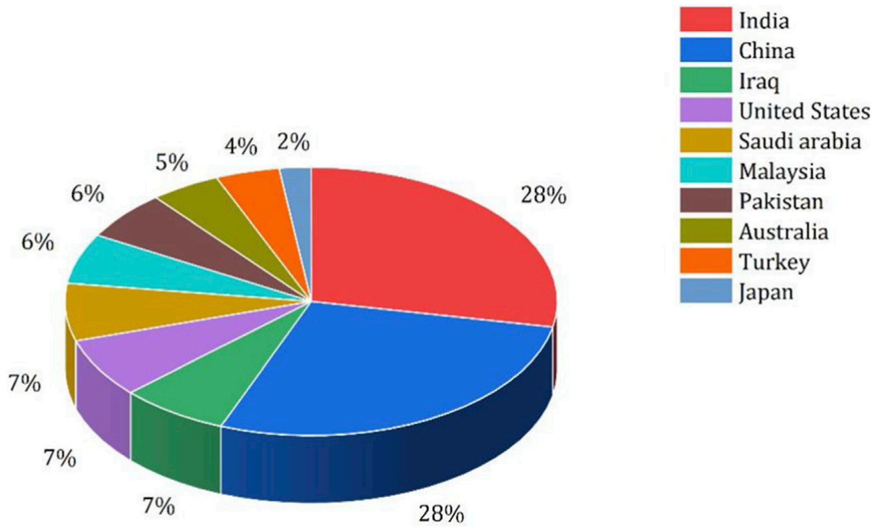


FIGURE 5
Country-wise publication.

TABLE 2 Top 10 Journals from SCOPUS search with research on artificial aggregate.

Source title	No. of articles	Publisher	Scopus cite score 2025
Construction and Building Materials	43	Elsevier	13.1
Materials	26	Multidisciplinary Digital Publishing Institute (MDPI)	6.3
Lecture Notes in Civil Engineering	21	Springer Nature	0.5
Asian Journal of Civil Engineering	19	Springer Nature	5.1
Journal of Building Engineering	17	Elsevier	11.9
AIP Conference Proceedings	14	American Institute of Physics	0.6
Iop Conference Series Earth and Environmental Science	14	Institute of Physics Publishing	1.3
Materials Today Proceedings	13	Elsevier	7.4
Buildings	12	Multidisciplinary Digital Publishing Institute (MDPI)	5.0
Case Studies in Construction Materials	11	Elsevier	10.8
Innovative Infrastructure Solutions	10	Springer Nature	4.2
Scientific Reports	9	Springer Nature	5.7
Journal of Cleaner Production	8	Elsevier	19.3

that maximizes the reuse of industrial byproducts while producing strong pellets, formation of pellets as shown in Figure 7.

4.1.3 Agglomeration mechanism and pellets growth stages

Agglomeration is a controlled process of pellet formation, in which fine materials and binders are combined in a rotating drum or disc. Seed particles form and grow through coalescence and layering (Ragavendra et al., 2021). Factors such as drum speed, angle, and moisture content significantly influence the properties of the final aggregate. In certain cases, the sintering process follows pelletization, during which high-temperature reactions enhance particle bonding and strength.

Artificial aggregates offer numerous advantages over natural aggregates, enhancing both the mechanical properties and the durability of concrete structures (Farooq et al., 2023). They mitigate water penetration, shrinkages, and cracking, thereby improving dimensional stability and extending the service life of structures (Mathew et al., 2023).

In the summary, artificial aggregates can be produced through crushing, pelletization, agglomeration, molding, or hand shaping. While molding and hand shaping are mainly limited to laboratory studies, crushing produces angular particles commonly used in

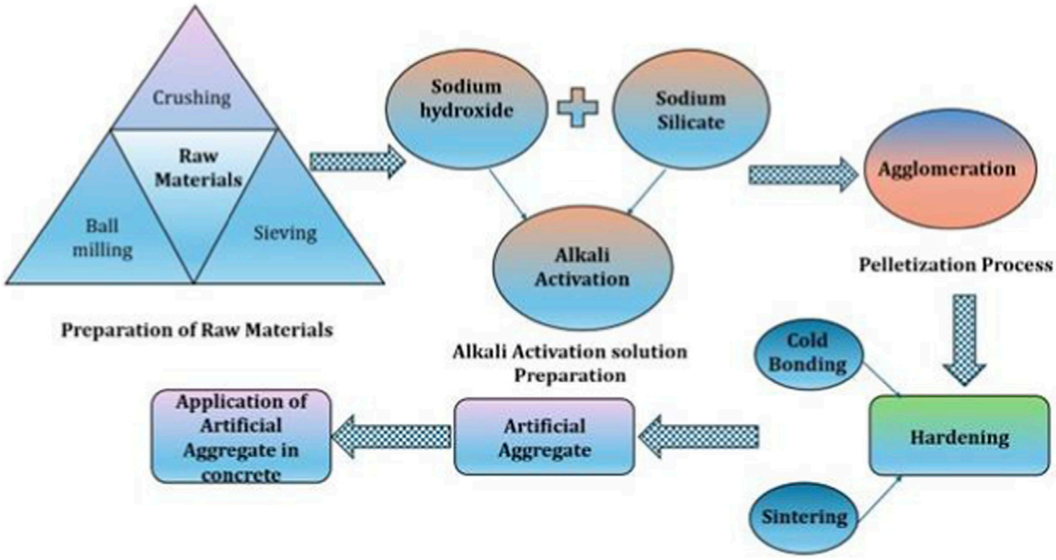


FIGURE 6
Process of making artificial aggregates.

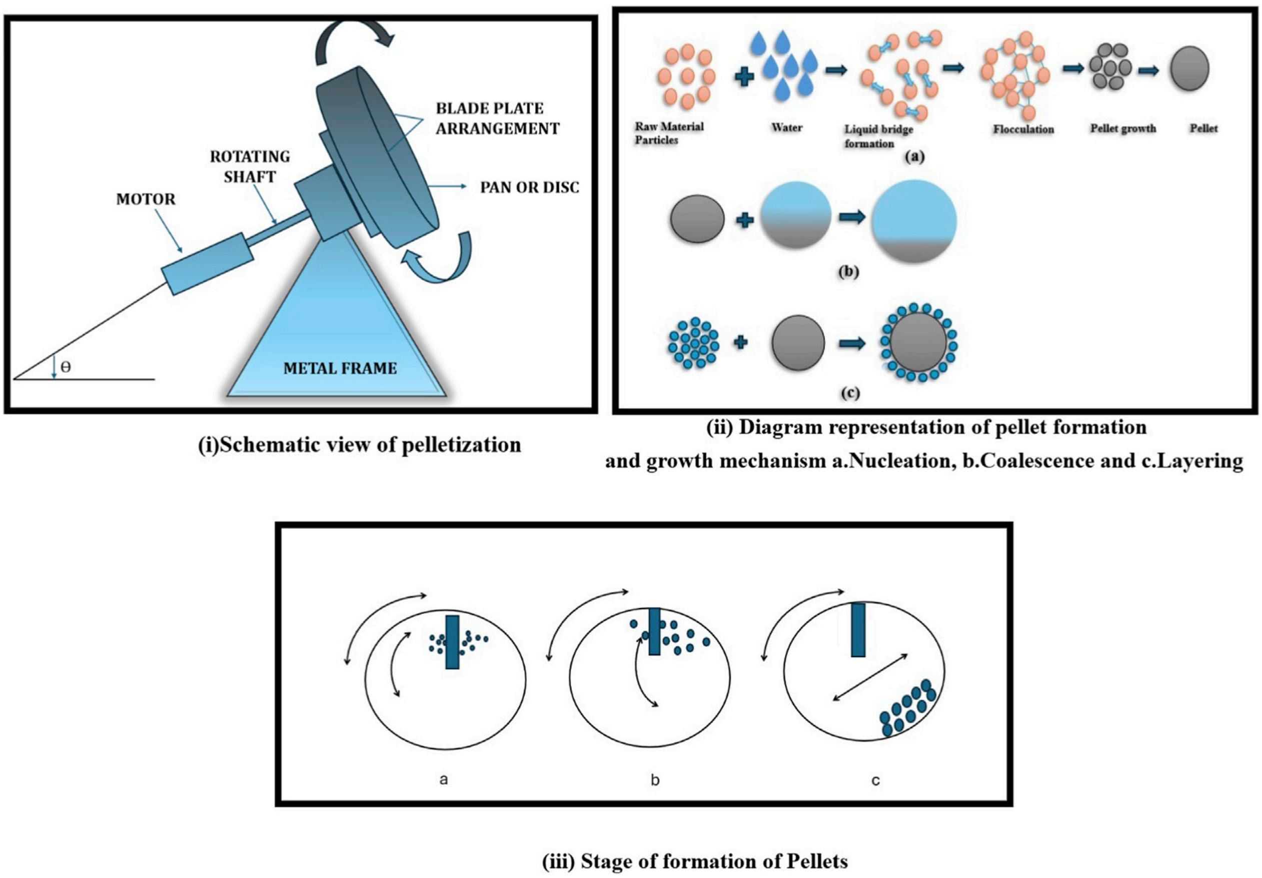


FIGURE 7
Formation of pellets.

industry. Under controlled conditions, pelletization efficiently converts fine industrial by-products into strong, spherical aggregates, ensuring consistent size and strength. Agglomeration enhances large-scale production by precisely regulating aggregate formation. These methods promote sustainability by recycling industrial waste and reducing dependence on natural aggregates.

5 Classification and characteristics of artificial aggregates

This review thoroughly examined and assessed sustainable artificial aggregates made from industrial residues and debris. The research articles included were chosen based on predetermined parameters that incorporated aggregate types and application advances.

5.1 Sintered fly ash

Sintered fly ash aggregates (SFA) are produced by heating a mixture of fly ash and clay at temperatures ranging from 900 °C to 1,250 °C, resulting in aggregates that are lightweight and porous, yet strong and durable. The best properties are observed around 1,100 °C, where the aggregates exhibit minimal water absorption and a stable structure. The method decreases the dead weight in construction and promotes environmental sustainability by repurposing fly ash waste.

5.2 Alkali-activated aggregates

Alkali-activated aggregates are an advancement in sustainable construction materials, produced by reacting aluminosilicate-rich industrial byproducts with alkaline solutions such as sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3). The Na_2SiO_3/NaOH ratio has a significant influence on aggregate properties. An optimal ratio of 2.5 results in low water absorption, dense microstructures, and uniform spherical particles, making them promising eco-friendly substitutes for natural aggregates. A lower ratio (2.0) results in slow granulation, and a higher ratio (≥3.0) results in irregularly shaped particles. Optimizing the composition of the activator ensures high-quality, eco-friendly aggregates suitable for sustainable construction.

5.3 Autoclaved aggregates

Autoclaved aggregates are produced from lime and silica-rich materials subjected to high-pressure curing in autoclaves. This process improves the microstructure of the aggregates, which makes them more stable in size, better at keeping heat in, and less likely to shrink. For instance, quartz tailings have been effectively converted into lightweight aggregates (<1,100 kg/m^3) through autoclaving at 195 °C and 1.38 MPa, where the controlled addition of aluminum powder generates a cellular framework that significantly improves both thermal efficiency and acoustic resistance, making them suitable for prefabricated panels and energy-efficient construction applications.

5.4 Cold bonding aggregates

Cold bonding is an economical and eco-friendly technique for creating artificial aggregates. It involves the aggregation of fine particles at room temperature using cement-based or alkaline binders. A standard curing duration of 28 days at ambient temperature is essential to guarantee sufficient hydration, densification, and strength enhancement. Recent research suggests that incorporating nano-SiO_2 can further enhance the microstructure and mechanical properties of cold bonding aggregates, increasing their viability as sustainable alternatives to natural materials in various construction applications. Their adaptability makes them suitable for lightweight concrete, floating structures, landscaping, and other eco-friendly building systems, supporting the transition toward durable and low-carbon construction practices.

5.5 Lightweight aggregates

Lightweight aggregates have emerged as an essential element in modern construction, facilitating the production of concrete that is lighter while retaining the requisite strength for safe and durable structures. The incorporation of these materials offers several practical benefits, including reducing the weight of buildings, enhancing thermal comfort, improving durability, and simplifying the handling and transportation of concrete onsite.

5.6 Heavyweight aggregate

Heavyweight aggregates (HWA) are employed to produce high-density concrete, typically ranging from 3000 to 6000 kg/m^3. They are mainly sourced from dense minerals such as barite, magnetite, and hematite, or from industrial by-products like steel residues and ferrochrome slag.

This review highlights that artificial aggregates offer a range of sustainable alternatives to natural aggregates, each produced through specific techniques that enhance performance and environmental benefits. Sintered and alkali-activated aggregates show exceptional strength and durability, whereas autoclaved and cold-bonded aggregates provide energy-efficient production techniques. Lightweight and heavyweight aggregates are designed for particular structural applications.

6 Resource efficiency and sustainable material utilization

This section comprehensively presents studies on the manufacturing of artificial aggregates from waste and industrial residues. The effects of the surrounding and mechanical properties were used to select research work on sustainable aggregate materials for production.

This methodology reduces carbon footprints, conserves natural resources, and promotes sustainable construction practices (Puri et al., 2022). These materials significantly minimize environmental pollution and the amount of waste sent to landfills while offering excellent performance as natural aggregates alternatives (Hadavand and Imaninasab, 2019). Artificial aggregates can be derived from various sources, including fly ash, blast furnace slag, recycled aggregates, steel slag, rice husk ash, glass waste, plastic waste, minimized residues, ferrochrome slag, copper slag, and municipal solid waste incineration bottom ash (MSWIBA).

6.1 Fly ash

Fly ash is a fine powder obtained from thermal power plants (Huang et al., 2007). It is primarily composed of SiO_2, Al_2O_3, Fe_2O_3, and CaO (Hunag et al., 2015). Fly ash aggregate may reduce global warming potential (GWP) in the range of approximately 45%-60% compared to conventional aggregate due to waste reduction and lower embodied energy (Kockal and Ozturan, 2010; Puri et al., 2022). An aggregate impact value (AIV) of 12%-28%, reflecting differences in curing conditions (Huang et al., 2007). Fly ash aggregates are lightweight and slightly durable. Water absorption rates between 8%-13% they exhibit relatively high porosity, which enhances lightweight characteristics but may limit durability in aggressive environments.SEM imaging at ×2,300 magnification shows a thick structure of needle-shaped ettringite crystals intertwined with amorphous C-S-H gel, indicating extensive geopolymer materials hydration and pore filling. They are suitable for lightweight, durable concrete applications due to their spherical, porous particles, amorphous glassy phases with quartz and mullite crystals, and high silica-alumina content (Kockal and Ozturan, 2010).

6.2 Blast furnace slag (BFS)

Blast furnace slag is a byproduct of iron production, consists of SiO_2, CaO, Al_2O_3, MgO, and Fe_2O_3 (Ferone et al., 2013). GGBFS enhances durability, reduces heat generation during hydration, and improves resistance to chemical degradation (Chelluri and Hossiney, 2024; Ibrahim and Atmaca, 2023; Uppalapati et al., 2020; Vollpracht et al., 2018; Ragavendra et al., 2021). The ASTM C989/C989M specifications govern GGBFS. It exhibits 14.6% impact strength and toughness, resisting abrupt loads. Reported water absorption is 4.1%, which is lower than that of fly ash aggregates, contributing to improved interfacial bonding. The combination of strength, durability, and sustainability makes GGBS aggregates particularly suitable for construction purposes. GGBFS-based aggregates show a GWP reduction of 30%-50% and minimize energy use since they utilize metallurgical waste that requires less treatment than virgin aggregates (Razak et al., 2023).

6.3 Recycled aggregate

Recycled aggregates are generated through the processing of construction and demolition waste (Kursula et al., 2022; Rajalekshmi and Jose, 2023). It generally exhibits higher porosity, and water absorption is 6.8% compared to natural aggregates (Su et al., 2023). Research indicates a reduction in compressive strength ranging from 4% to 8% at replacement levels between 50%-100%, and a decrease in tensile strength and elastic modulus from 9.5% to 40% has been reported (Zhao and Zhang, 2024). While some studies suggest a 30%-65% reduction in greenhouse gas emissions, the performance of recycled aggregates varies significantly due to the heterogeneity of source materials and the quality of processing, highlighting the need for improved treatment and quality control strategies (Wang et al., 2025).

6.4 Steel slag

Steel slag is produced as a byproduct in the steel manufacturing process (Sivakrishna et al., 2020). It comprises calcium and silicon oxides, along with mineral phases like C_3S and C_2S, which impart cementitious properties (Suhendro, 2014). Research indicates that steel slag aggregate enhances mechanical performance, with compressive and tensile strength increases of approximately 6%-8% compared to natural aggregates (Ren and Li, 2023). Although a reduction in GWP ranges from 25% to 45% has been observed; however, elevated water absorption is 3%-6.4% and volumetric instability remains a critical challenge (Brand and Roesler, 2015; Elibol and Sengul, 2016; Guan and Zhou, 2025). To address the expansion risks, proper aging or stabilization is essential to mitigate expansion risks, limiting immediate large-scale adoption without further processing.

6.5 Rice husk ash

RHA, which is mainly amorphous silica, is produced by burning rice husks (Alabi and Mahachi, 2022; Kumar Das et al., 2022). RHA can be combined with clay, glass powder, and binders to produce lightweight aggregates. After sintering at around 1,000 °C, the resulting aggregates are porous, light, and environmentally friendly, making them suitable for non-structural concrete applications. It absorbs 20%–29% more water than conventional aggregates, requiring careful water management. At ideal replacement levels of 5%-10%, a 1,000-micron SEM displays a dense geopolymer binder matrix with submicron rice husk ash components, showing preliminary C-S-H gel precipitation and microcrack development at interface boundaries (Wang et al., 2023).

6.6 Glass waste

Recycled glass aggregate primarily consists of silica (approximately 70%) and sodium, calcium, and aluminum oxides (Shaiksha Vali and Murugan, 2017). Glass-based aggregates exhibit low water absorption, which ranges from 0.1% to 0.7%, and they can enhance flextural performance when used as a replacement in the range of 20%-30%. However, excessive replacement leads to reduced bonding due to smooth particle surfaces, which limits their structural application without surface modification or hybridization strategies (Harrison et al., 2020).

6.7 Recycled plastic

Plastic aggregates reduce the need for virgin aggregates while enhancing the ductility and flexibility of concrete. It generally exhibits lower compressive strength, with reported values around 20-25 MPa at 28 days of 15% substitution of natural aggregate, which makes them appropriate for non-structural lightweight applications (del Rey Castillo et al., 2020; Saikia and De Brito, 2012). Impact resistance can drop 5%–15% after repeated recycling cycles, while some formulations remain stable. Water absorption of recycled plastics is normally 0.12%–0.66%, although some composites can absorb up to 7.7% after prolonged immersion, reducing tensile and impact strength (Islam et al., 2024).

6.8 Mining waste

Mine tailings and other mining residues can be repurposed into aggregates to mitigate environmental pollution and conserve resources (Ostrowski et al., 2020; Yliniemi et al., 2017). If replacement levels exceed 30%, mining waste aggregates have compressive strengths that are 10%–15% lower than natural aggregates. Mining waste aggregates absorb 3%–8% more water than natural aggregates. SEM at 100,00x after 28 days at 40 °C shows a dense, weakly crystalline geopolymer material matrix with fiber C-S-H gel and unreacted precursor particles, suggesting continued hydration and pore refinement. Due to voids and reduced interfacial adhesion, toughness is 5%-10% lower than natural aggregates (Nguyen et al., 2023).

6.9 Ferrochrome slag

As a byproduct of ferrochrome alloy production, ferrochrome slag exhibits physical and mechanical properties similar to those of natural aggregates (Al Hindasi et al., 2025). It has a specific gravity of 3.0, which is higher than that of natural aggregates (2.81). This means that it is denser. Ferrochrome slag has higher impact and crushing strengths than natural aggregates. FCS was used to replace up to 75% of traditional coarse aggregate, increasing compressive strength from 34 MPa to 48 MPa and split tensile strength by 49% (Al Hindasi et al., 2025; Issa Fares et al., 2023). The SEM analysis shows a blend of angular polymeric fragments and microcrystalline binding components, indicating poor agglomeration and varied particle sizes (Issa Fares et al., 2023).

6.10 Copper slag

Research indicates that substituting 60% of natural aggregate with copper slag can enhance compressive strength by 31%, flexural strength by 19%, and tensile strength by 18% (Filipović et al., 2021; Khalil et al., 2018). Its high specific gravity of 3.3 and low water absorption of 0.65% increase concrete density and reduce permeability. Adding copper slag coarse aggregate to concrete can enhance its impact strength and toughness by up to 27%. A 10,000-micron SEM image reveals a textured matrix containing angular geopolymer material segments and microcrystalline hydration products, exhibiting surface roughness that enhances interparticle mechanical interlocking (Sharifi et al., 2020).

6.11 Municipal solid waste incineration bottom ash (MSWIBA)

MSWIBA from municipal waste incineration can serve as a partial substitute for natural aggregates (Saad et al., 2019). These replacements conserve natural resources and reduce landfill waste. MSWIBA differs in composition and may include heavy metals; therefore, it must be treated before use (Kogbara et al., 2024; Oyejobi et al., 2024). MSWIBA, used as coarse aggregate, has a compressive strength range of 17–36 MPa and 4% water absorption due to its porous and heterogeneous character. MSWIBA concrete resists freeze-thaw cycles and sulfate attack; however, untreated metallic aluminum content can expand, necessitating pre-treatment before structural use.

Overall, waste-derived artificial aggregates exhibit significant potential for sustainable construction; however, reported mechanical and environmental benefits are highly contingent on specific conditions. Slag-based systems generally offer superior mechanical performance, while fly ash and polymer-based aggregates tend to offer environmental benefits, though this often comes at the cost of reduced structural integrity. While the literature indicates promising mechanical and environmental potential for waste-derived artificial aggregates, reported performance varies widely across studies, emphasizing the importance of establishing standardized evaluation methods and large-scale validation (Ling et al., 2023; Nguyen et al., 2023).

Table 3 shows the types and properties of various kinds of aggregate composite compositions. Also, it highlights the comparison between different materials, and it showcases their distinct characteristics and properties (Juenger et al., 2011; Shaiksha Vali and Murugan, 2017).

7 Physical properties of artificial coarse aggregate

A comprehensive assessment of peer-reviewed studies on artificial coarse aggregate physical characteristics was conducted. The qualities investigated are specific gravity, water absorption, and mechanical strength.

7.1 Water absorption

The role of water absorption is significant in evaluating the effectiveness of artificial aggregates within concrete (Almadani et al., 2022; Ibrahim et al., 2022; Terzić et al., 2015). The porous nature of artificial aggregates enables them to absorb between 5% and 25% of their weight in water, depending on the raw materials and production methods. Although a higher absorption rate can limit the water available for cement hydration, it also enhances freeze-thaw resistance, bonding, and overall durability (Gesoğlu et al., 2012).

7.2 Specific gravity

The specific gravity of aggregates has a significant impact on the design of concrete mixtures and the weight of the resulting structure. Artificial aggregates typically exhibit a specific gravity ranging from 1.6 to 2.2, which is lower than that of natural aggregates due to their porous characteristics (Terzić et al., 2015; Usanova and Barabanshchikov, 2020). This lower density makes them particularly advantageous for use in lightweight concrete, as it helps to reduce the dead load of structures.

TABLE 3 Chemical composition of various sources of materials.

Oxide (%)	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	P_2O_5	TiO_2	Cl	LOI	$CaCO_3$	Moisture	Carbon	Specific gravity	References
Fly ash	37.8-62.9	19.9-30.61	3-11.4	1.67-17	0.54-2.88	0.27-8	0.05-0.87	0.11-2.77	0.5	0.8	0.0124	0.86-8.95	-	-	-	2.4-2.67	Shaiksha Vali and Murugan (2017)
Mine Tailing	49.8-25.3	10.7-7.0	-	11.7-10.9	6.7-6.6	4-13.6	3.1	1.3-0.8	0.2-0.1	1.3-0.4	-	0.2-8.8	-	0.2-0.3	-	-	Yliniemi et al. (2017)
Red clay	57.5	17.28	6.03	7.08	1.71	1.35	1.46	1.78	-	0.673	-	5.54	-	15.84	-	1.65	Islam et al. (2024)
Savar clay	64.24	9.35	1.81	2.59	3.33	2.13	2.2	5.38	-	0.582	-	8.38	-	16.32	-	1.81	
Rice Husk Ash	88.74	0.76	0.24	0.18	0.54	1.07	1.6	3.23	-	0.09	-	3.555	-	13.58	-	1.90	
Waste Glass powder	79.05	1.54	0.12	4.96	0.62	0.18	13.1	0.34	-	0.085	-	-	-	0.06	-	2.11	
Micro Silica	94.22	0.24	0.85	0.76	0.34	0.13	0.57	0.18	-	-	-	2.33	-	-	-	2.2	Abbas et al. (2024)
GGBS	36.7	16.6	0.45	35.1	6.11	1.27	0.2	0.53	0.06	0.92	-	-	-	-	-	2.86	Vignesh and Abdul Rahim (2024)
Metakaolin	53	43.5	0.91	0.31	-	0.1	0.17	0.16	0.11	1.49	-	-	-	-	-	2.62	
Lime Powder	1.27	0.17	0.09	94.4	2.48	0.4	-	-	-	-	-	-	-	-	-	2.34	
Palm oil Boiler Ash	50.30	2.49	5.19	19.70	1.96	0.70	-	12.90	4.98	-	-	1.25	---	-	-	-	Ling et al. (2023)
Mining residues	56.3	14.4	6.8	5.1	4.2	-	1.4	1.6	-	-	-	-	-	-	-	-	Huang et al. (2007)
Heavy Metal Sludge	45.1	13.0	4.8	19.6	0.9	-	2.1	1.2	-	-	-	-	-	-	-	-	
Incinerator fly ash	30.3	10.3	12.0	33.9	1.2	-	1.5	0.3	-	-	-	-	-	-	-	-	
Municipal Solid Waste Incineration Bottom Ash	70.9	8.5	5.87	3.69	1.14	0.16	4.24	1.97	-	-	-	-	-	-	-	-	Liu et al. (2022)

TABLE 4 Mechanical properties of aggregate concrete.

Year	Precursors	Post processing	Compressive strength	Flexural strength	Tensile strength	Inference	References
2020	Fly ash	Sintering	33.38-50.58	4.15-5.01	6.28-6.36	This study demonstrates that concrete incorporating sintered fly-ash aggregate and 0.25% basalt fiber is 12% more cost-effective than conventional concrete. The inclusion of fibre significantly enhances tensile and flexural strength and marginally improves compressive strength; however, it leads to a decrease in Young's modulus and durability	Divyah et al. (2020)
2022	Flyash, Cement	Cold Bonding	46- 48	5.41-6.62	-	This study effectively employed cold-bonded pelletization to produce synthetic lightweight aggregate (LWA) in waste materials (FA, GGBFS, QP). The findings indicate that incorporating these aggregates significantly improves the physical characteristics of concrete, with a 40% replacement of QP resulting in a 41% enhancement in compressive strength	Ibrahim et al. (2022)
	GGBFS, Cement	Cold bonding	44-51	4.48-5.54	-		
	Quartz Powder, Cement	Cold bonding	54-71	5.56-6.09	-		
2022	Washing Aggregate Sludge, GGBS, OPC	Cold bonding	48.9- 57.7	-	-	This study demonstrated the efficient utilization of washing aggregate sludge (WAS) through the manufacturing of cold-bonding and sintered artificial aggregates. When incorporated into concrete, these aggregates resulted in a lower oven-dry density while maintaining similar mechanical characteristics to conventional concrete	Özkan et al. (2022)
	Washing Aggregate Sludge, GGBS, OPC	Sintering	46.6-52.7	-	-		
2019	Fly ash	Sintering	23	2.7	3.38	This study effectively showed that the significant substitution of conventional concrete aggregates in fly ash cenosphere (FAC) as well as sintered fly ash aggregate (SFA) may produce environmentally friendly, sustainable lightweight concrete (LWC) that meets ACI standards. However, issues related to increased absorption of water and permeable pores require additional research into durability and microstructure	Satpathy et al. (2019)
2018	Bentonite Clay	Ambient Curing	32.8-35.8	4.6-5.5	2.22-2.59	This study effectively developed a highly durable, insulation structural light-weight geopolymer concrete (LWGPC) utilising low calcium fly ash and bentonite clay for the synthetic light-weight aggregate, resulting in compressive strength of 35.8 MPa and a thermal conductivity of 0.9567 W/(m.k) at 28 days	Abbas et al. (2018)
2015	Fly ash, quarry Dust, and Cement	Cold Bonding	20-30	-	2.18-3.00	Using fly ash and quarry dust as a binder, this study successfully produced cold-bonded artificial coarse aggregates. It also showed that these aggregates could be used to create sustainable concrete with strengths of up to 30 MPa and a progressive slump loss	Thomas and Harilal (2015)

(*Continued*)

TABLE 4 Continued

Year	Precursors	Post processing	Compressive strength	Flexural strength	Tensile strength	Inference	References
2015	Municipal solid waste incinerator, fly ash	Cold Bonding	18-34	-	-	This study effectively showed that it is possible to recycle fly ash from hazardous waste from municipal incinerators into lightweight, porous aggregates using a two-stage cold-bonded pelleting method (using up to 70% ash). The materials produced are appropriate for light-weight concrete with average performance and improved stabilisation efficiency	Colangelo et al. (2015)
2015	Fly ash, bentonite	Sintering	27.87-41.32	3.3-4.3	2.4-2.5	This study found that lightweight aggregates made of sintered fly ash produced greater mechanical properties in concrete than cold-bonded aggregates. The ideal mix, which included 62% substitution, had an effective compressive value of 39.97 MPa when cured in hot water and generally showed positive strength increases when cured in accelerated conditions	Gomathi and Sivakumar (2015)
	Fly ash, bentonite	Cold bonding	19.43-25.11	2.10-2.20	2.26-2.94		
2015	Fly ash	Sintering	28.87-52.64	2.62-4.45	-	In this study, pelletized fly ash aggregates optimised through mechanical activation and sintering were used to successfully create high-performance lightweight concrete (LWC). The resulting mechanical and physical properties matched those of normal-weight concrete, confirming a sustainable reuse of waste materials	Terzić et al. (2015)
2013	Cement Kiln dust, GGBS, Marble Sludge	Cold Bonding	22.5-41.8	-	-	To create lightweight concrete by replacing natural aggregates, this research effectively employed a cold-bonded pelletization process to create environmentally friendly synthetic lightweight aggregates in industrial byproducts (cement kiln debris, slag, as well as marble sludge), demonstrating the feasibility of this recycling technique	Colangelo and Cioffi (2013)
2013	Sewage sludge and glass powder	Sintering	49.46	-	-	In this study, wet sewage sludge and waste glass were successfully converted into high-grade lightweight aggregate (LWA). The ideal waste glass addition ratio was 30-50 percent. The LWA generated outstanding concrete, outstanding workability, and a notable compressive value of 49 MPa on 28 days when employed in concrete	Tuan et al. (2013)

(*Continued*)

TABLE 4 Continued

Year	Precursors	Post processing	Compressive strength	Flexural strength	Tensile strength	Inference	References
2012	Fly ash, GGBS, Rice husk	Cold bonding	14.8-38.1	-	-	This study effectively produced cement-free cold-bonding lightweight aggregates (LWA) in fly ash (FA) accelerated by GGBS and RHA. Both the binary as well as ternary blends produced high-performance light-weight concrete (HPLWC) with compressive values up to 38.1 MPa and significantly increased the crushing strength of LWA (up to 15.7 MPa)	Bui et al. (2012)
2012	Cement, Fly ash, GGBS	Cold Bonding	28-50	-	-	This study successfully created lightweight cold bonding aggregates (LWAs) with slag and fly ash. It was discovered that optimal cement content had a significant impact on LWA strength and, in consequence, LWC performance. The best mix of 20% OPC, 40% slag, and FA LWA produced the maximum 56-day compressible strength of concrete of 51 MPa	Gesoğlu et al. (2012)
2007	Fly ash	Alkali activator	26.7	-	-	Alkali-activated fly ash paste can produce non-hazardous lightweight aggregate (AFLA), as demonstrated by the concrete's remarkable 26.47 MPa strength at compression and freeze-thaw resilience	Jo et al. (2007)
2010	Fly ash, Bentonite, Glass powder	Sintering	42.3 to 55.8	-	3.7-3.9	Fly ash-based lightweight concrete (LWC) showed similar freezing and thawing resilience to normal-weight concrete (NWC). Additionally, the concrete's mechanical qualities (split tensile and compressive) improved proportionately with oven-dry density and were comparable to NWC.	Kockal and Ozturan (2010)
2014	Fly ash, GGBS	Alkali activation	17.80-25.40	1.95-4.01	2.77-3.6	The concrete with the maximum crushing value (22.81 MPa) and compressive strength (31.98 MPa) was created by activating the GGBS-Fly ash aggregate of 10 Molarity. This research showed how to successfully produce synthetic artificial aggregate by pelletizer using a variety of inhibitors (bentonite, GGBS, and metakaolin) and alkaline activation	Gomathi and Sivakumar (2014)
	Fly ash, Metakolin	Alkali activation	14-20	1.56-2.04	2.12-3.41		
	Fly ash, Bentonite	Alkali activation	12-24	1.83-2.24	2.65-3.52		

7.3 Crushing and impact strength

The ability of an aggregate to withstand compressive forces is indicated by its crushing strength, which has a direct impact on concrete's overall strength. The impact strength of these aggregates, measured by the Aggregate Impact Value (AIV), shows their capacity to resist sudden forces. High-quality aggregates typically have an AIV below 20%, whereas values exceeding 30% indicate weaker performance. These attributes are essential in evaluating the durability and structural reliability of artificial aggregates in construction projects (Kurzekar et al., 2024; Terzić et al., 2015).

This study indicates that certain physical features of artificial coarse particles considerably affect concrete performance and durability. Depending on raw materials and manufacturing techniques, water absorption ranges from 5% to 25% by weight. Due to their porous nature, the specific gravity is lower than conventional aggregates (1.6–2.2), affecting the mix proportion, workability, and weight of the structure.

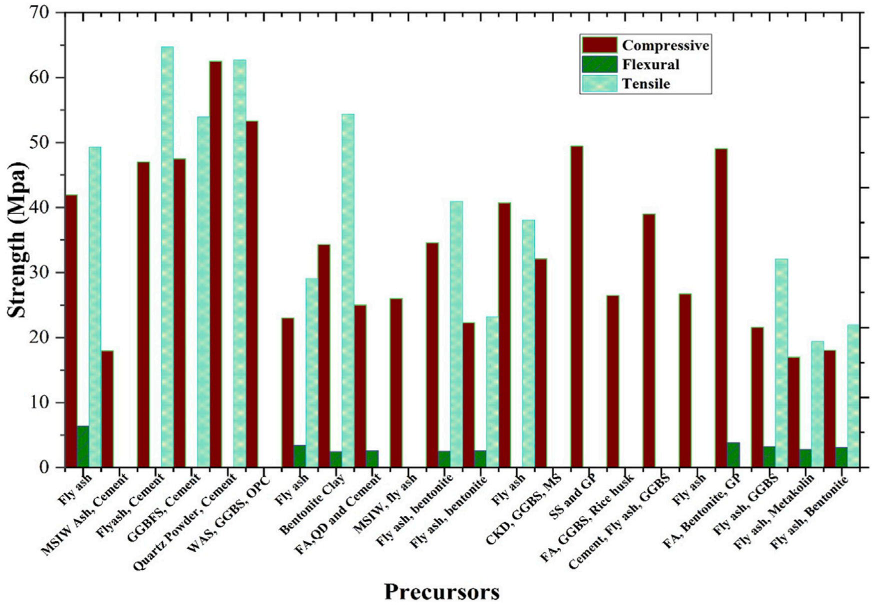


FIGURE 8
Mechanical strength comparison of artificial aggregates from different precursors.

8 Mechanical properties of aggregate concrete

This comprehensive review consolidates findings from current research on the tensile, flexural, and compressive strengths of concrete incorporating artificial aggregates.

8.1 Compressive strength

The compressive strength of concrete with artificial aggregates ranges from 15.94 to 77.5 MPa, indicating suitability for lightweight concrete (LWC) applications. Sintered and alkali-activated aggregates can achieve strengths comparable to those of normal-weight concrete (NWC) (Terzić et al., 2015). Additionally, mix design parameters, including the water-to-binder ratio, aggregate proportion, and curing method, are critical in customizing artificial aggregates to produce concrete that is both durable and structurally sound (Gomathi and Sivakumar, 2014; 2015; Kockal and Ozturan, 2010; Nadesan and Dinakar, 2018; Thomas and Harilal, 2015).

8.2 Tensile strength and flexural strength

The split tensile strength of artificial aggregate concrete ranges from 1.54 to 4.01 MPa, while the flexural strength varies between 2.12 and 5.5 MPa, both of which are closely associated with compressive strength. These mechanical properties are primarily influenced by the quality of the mortar, aggregate strength, and interfacial transition zone (ITZ) (Chang et al., 1996). An increased proportion of artificial aggregates may lead to a reduction in tensile strength, as cracks frequently originate within the aggregates. Flexural strength is enhanced by a denser mortar matrix and a reduced aggregate content, as the mortar plays a crucial role in resisting bending stresses (Abbas et al., 2018; Gomathi & Sivakumar, 2015; Kockal and Ozturan, 2010; Terzić et al., 2015; Thomas and Harilal, 2015). Table 4 shows the mechanical properties of artificial aggregate concrete. Figure 8 shows a comparison of the mechanical strength of artificial aggregate concrete with various precursors.

The section indicates that concrete made with artificial aggregates can have compressive strengths ranging from 15.94 to 77.5 MPa. The quality of the aggregates, the mix design parameters, and the curing conditions are the main factors that affect this. Sintered and alkali-activated aggregates typically offer better performance. Tensile strength, ranging from 1.54 to 4.01 MPa, and flexural strength, from 2.12 to 5.5 MPa, are more dependent on the properties of the mortar and the quality of the interfacial transition zone (ITZ). Overuse of artificial aggregates may decrease tensile capacity, while a denser mortar matrix and optimized aggregate proportions can improve flexural performance.

9 Conclusion

The present article provides a comprehensive evaluation of studies on the concept of artificial aggregate in the construction industry.

- Industrial byproduct-based artificial aggregates have a 60%–85% lower global warming potential than conventional aggregates due to cold bonding, lowering fuel use, and CO_2 emissions.
- Cold bonding uses 60%-85% less energy than sintering. This process produces aggregates with less porosity and 20%–35% more compressive strength. In cold bonding, the alkali-activated binding agent limits capillaries and provides denser hydration products. Furthermore, artificial aggregates drastically reduced the consumption of virgin raw materials.

- Artificial aggregates made with geopolymer and cold bonding perform better. Compressive strength is 15.94–77.5 MPa, specific gravity is 15%–38% lower than conventional aggregates, and CO_2 emissions are 57.6% when 75% substituted with conventional aggregates.
- Alkali activation improves artificial aggregate mechanical performance and durability by creating a dense microstructure with better interfacial transition zones.
- Fly ash-derived aggregates exhibit excellent compressive strength (up to 78 MPa) due to their spherical morphology and pozzolanic reaction, followed by GGBFS-derived aggregates (60-70 MPa) with a latent hydraulic glassy phase and steel slag aggregates (50-68 MPa) with dense metallurgy.

This systematic review offers a critical synthesis of artificial aggregate technologies that utilize industrial by-products, focusing on the trade-offs between environmental benefits and mechanical strength in both traditional and innovative methods. Slag-based systems typically exhibit higher strength, whereas fly ash and polymer-based aggregates offer sustainability benefits with reduced structural capacity. Alkali-activated aggregates that integrate multiple waste materials, particularly those combining cupola slag and GGBS, remain underexplored and require further investigation to evaluate their durability, cost-effectiveness, and scalability. The absence of standardized testing protocols and large-scale evidence continues to impede direct comparison and practical implementation.

10 Limitation

The present study exclusively examined papers located in SCOPUS articles. Despite the extensive nature of the SCOPUS database. In comparison to alternative methods, such as Web of Science, the SCOPUS database may still overlook research disseminated through channels not represented in SCOPUS journals.

11 Future scope

Future artificial aggregate research includes transformative manufacturing, nanotechnology integration, and sustainable production approaches. Smart manufacturing techniques using machine learning algorithms can optimize production parameters in real time, reduce energy consumption by 25%–30%, and improve quality consistency. 3D printing technologies can create custom aggregate geometries with improved interlocking mechanisms. Further research should focus on life cycle optimization, predictive models utilizing physics-informed neural networks, and performance-based standards that account for waste-derived material variability and structural reliability. Digitalization, circular economy concepts, and enhanced characterization methods require high-performance, multifunctional artificial aggregates for sustainable infrastructure development.

Data availability statement

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

Author contributions

PS: Data curation, Validation, Conceptualization, Methodology, Resources, Writing – original draft. TM: Supervision, Writing – review and editing.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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The author(s) declared that generative AI was not used in the creation of this manuscript.

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