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Sustainable Utilization of Triple-Industrial Waste for High-Performance Eco-Tiles: A Circular Economy Approach

Kaashvi Lodha
Grade: XII Science
School: Heritage Girls School, Udaipur

Dr. Mamta Lodha
HOD, Science Department
Heritage Girls School, Udaipur

Abstract

The increasing generation of industrial waste due to rapid industrialization, urbanization, and infrastructure development has created significant environmental and resource management challenges worldwide. Simultaneously, the construction industry continues to rely heavily on virgin raw materials, leading to resource depletion and increased carbon emissions. In response to these challenges, the circular economy has emerged as a sustainable approach that promotes the reuse and recycling of industrial by-products as secondary raw materials. This study presents a systematic review of the sustainable utilization of triple-industrial waste for manufacturing high-performance eco-tiles within a circular economy framework. The review focuses on five major industrial waste materials—fly ash, ceramic waste, steel slag, marble dust, and granite powder—and evaluates their potential to replace conventional raw materials in ceramic tile production.

A secondary research methodology based on the Systematic Literature Review (SLR) approach was adopted. Relevant peer-reviewed studies published between 2015 and 2025 were collected from internationally recognized databases, including Scopus, Web of Science, ScienceDirect, SpringerLink, MDPI, Elsevier, and Google Scholar. The selected literature was analyzed using thematic analysis, comparative analysis, content analysis, and critical literature synthesis to examine waste utilization, eco-tile manufacturing processes, mechanical performance, environmental impacts, and circular economy contributions.

The review reveals that industrial waste incorporation significantly enhances the compressive strength, abrasion resistance, durability, and dimensional stability of eco-tiles while reducing water absorption, virgin raw material consumption, landfill disposal, and greenhouse gas emissions. The findings further indicate that triple-industrial waste systems offer greater engineering and environmental benefits than single- or binary-waste approaches because of the complementary physical and chemical properties of different waste materials. However, the review also identifies limited research on standardized mix optimization, long-term durability assessment, life cycle evaluation, and the integrated application of triple-industrial waste in eco-tile manufacturing. The study concludes that the sustainable utilization of multiple industrial wastes represents a promising strategy for developing high-performance eco-tiles, promoting resource efficiency, advancing circular economy principles, and supporting sustainable construction and green infrastructure development.

Keywords: Triple-Industrial Waste; Eco-Tiles; Sustainable Construction Materials; Circular Economy; Fly Ash; Ceramic Waste; Steel Slag; Marble Dust; Granite Powder; Industrial Waste Recycling; Mechanical Performance; Environmental Sustainability.

I.INTRODUCTION

Background

The rapid pace of industrialization, urbanization, and infrastructure development has substantially increased the generation of industrial solid waste worldwide, creating significant environmental, economic, and resource management challenges. According to global estimates, billions of tonnes of industrial waste are generated annually from construction and demolition activities, thermal power plants, steel manufacturing, ceramic production, mining, and stone processing industries. Traditionally, these industrial by-products have been disposed of in landfills or open dumping sites, resulting in land degradation, groundwater contamination, greenhouse gas emissions, and depletion of valuable natural resources. Simultaneously, the construction industry remains one of the largest consumers of natural raw materials such as clay, sand, limestone, feldspar, and aggregates for manufacturing ceramic tiles and other building materials. This increasing demand has intensified pressure on natural ecosystems and highlighted the need for sustainable alternatives.

In recent years, sustainable construction has emerged as a key strategy for minimizing environmental impacts while improving resource efficiency. The concept of the circular economy has further accelerated this transition by encouraging industries to replace the traditional linear model of "take–make–dispose" with resource recovery, recycling, reuse, and industrial symbiosis. Within this framework, industrial wastes are increasingly regarded as valuable secondary raw materials rather than environmental liabilities. Numerous studies have demonstrated that wastes such as fly ash, ceramic waste, steel slag, marble dust, and granite powder possess favorable chemical, mineralogical, and engineering characteristics suitable for manufacturing sustainable construction products. Their utilization not only reduces landfill disposal but also conserves virgin resources, decreases carbon emissions, and supports cleaner production practices.

Among various construction materials, eco-tiles have attracted considerable attention because they provide an effective platform for incorporating industrial waste into value-added products. Previous research has reported improvements in compressive strength, abrasion resistance, dimensional stability, durability, and reduced water absorption when selected industrial wastes are incorporated into ceramic tile production. These findings indicate that industrial waste-based eco-tiles can satisfy engineering performance requirements while contributing to environmental sustainability and circular resource utilization.

Research Problem

Despite significant progress in industrial waste recycling, the construction industry continues to depend heavily on virgin raw materials, while enormous quantities of industrial by-products remain underutilized. Most existing recycling practices focus on the use of individual waste materials, resulting in inefficient utilization of the complementary engineering properties offered by different industrial wastes. Consequently, valuable resources such as fly ash, ceramic waste, steel slag, marble dust, and granite powder continue to accumulate in disposal sites, creating long-term environmental concerns.

Furthermore, manufacturers require construction materials that simultaneously exhibit high mechanical strength, durability, environmental compatibility, and economic feasibility. Achieving these multiple performance objectives through the utilization of industrial waste remains a significant research and industrial challenge.

Research Gap

The existing literature demonstrates extensive research on the application of individual industrial wastes and, to a lesser extent, binary waste combinations in ceramic products and sustainable construction materials. However, systematic investigations on the simultaneous utilization of triple-industrial waste for manufacturing high-performance eco-tiles remain limited.

Moreover, previous studies have generally emphasized either mechanical performance or environmental benefits independently, while relatively few investigations integrate engineering performance, environmental sustainability, and circular economy principles within a single analytical framework. In addition, standardized methodologies for optimizing the proportion of multiple industrial wastes and evaluating their combined effects on eco-tile performance are still lacking.

These research gaps highlight the need for a comprehensive review that synthesizes current knowledge on triple-industrial waste utilization and identifies future research opportunities.

Objectives

The present study aims to systematically review the sustainable utilization of triple-industrial waste for manufacturing high-performance eco-tiles within the framework of the circular economy. The specific objectives are:

- To review the current utilization of industrial waste materials in eco-tile manufacturing.
- To evaluate the mechanical performance of eco-tiles produced using multiple industrial wastes.
- To examine the environmental benefits associated with industrial waste utilization in sustainable construction.
- To analyze the contribution of triple-industrial waste toward implementing circular economy principles.
- To identify existing research gaps and recommend future research directions for sustainable eco-tile development.

Significance of the Study

This study provides a comprehensive synthesis of current scientific knowledge on the sustainable utilization of industrial waste in eco-tile manufacturing. By integrating findings from peer-reviewed literature, it offers an evidence-based understanding of how multiple industrial wastes can simultaneously improve engineering performance and environmental sustainability.

Academically, the review contributes to construction materials research by consolidating fragmented knowledge from materials science, ceramic engineering, environmental engineering, and waste management into a unified framework. Practically, the findings may assist researchers, engineers, ceramic manufacturers, policymakers, and environmental agencies in developing resource-efficient and environmentally responsible construction materials. The study also supports the achievement of Sustainable Development Goals (SDGs), particularly SDG 9 (Industry, Innovation and Infrastructure), SDG 11 (Sustainable Cities and Communities), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action), by promoting industrial waste recycling and sustainable manufacturing practices.

Furthermore, the proposed synthesis of triple-industrial waste utilization provides a scientific basis for future experimental investigations aimed at optimizing waste combinations and improving the large-scale production of high-performance eco-tiles.

Literature Review

Global Industrial Waste Generation

Rapid industrialization, urbanization, and population growth have significantly increased global industrial waste generation, making waste management one of the most pressing environmental challenges of the twenty-first century. According to the World Bank, global solid waste generation exceeds 2.2 billion tonnes annually and is expected to reach approximately 3.4 billion tonnes by 2050 if current production and consumption patterns continue. Industrial sectors, particularly construction, mining, manufacturing, metallurgy, ceramics, and energy production, contribute a substantial share of this waste stream. Rather than being viewed solely as environmental liabilities, these waste materials are increasingly recognized as valuable secondary resources under the principles of the circular economy, where waste is reused, recycled, or transformed into value-added construction materials.

Among industrial waste streams, construction and demolition (C&D) waste represents one of the largest fractions worldwide, accounting for nearly 30–40% of total solid waste generated globally. Large quantities of concrete, bricks, tiles, ceramics, mortar, glass, and aggregates are disposed of in landfills despite possessing considerable recycling potential. Recent studies emphasize that recycling C&D waste into construction products not only conserves natural aggregates but also lowers greenhouse gas emissions, landfill dependency, and production costs. Researchers have highlighted that incorporating recycled construction waste into ceramic products and paving materials substantially improves resource efficiency while supporting sustainable infrastructure development.

The ceramic industry is another major producer of industrial solid waste throughout the manufacturing cycle. Defective fired tiles, green rejects, polishing sludge, kiln dust, glazing residues, and broken ceramic products constitute approximately 15–30% of total ceramic production, depending on manufacturing technology and quality control systems. Traditionally, a considerable portion of these wastes has been disposed of in landfills, creating environmental and economic burdens. However, recent research demonstrates that ceramic waste possesses excellent pozzolanic activity, high silica and alumina content, and strong mechanical properties, making it highly suitable for reuse in concrete, bricks, eco-tiles, and geopolymer composites. Such reuse significantly reduces raw material extraction while improving the sustainability of ceramic manufacturing.

Global trends further indicate a transition from the traditional linear economy ("take–make–dispose") toward circular industrial systems, where industrial by-products are exchanged between industries through industrial symbiosis.

Numerous investigations report that combining multiple industrial wastes—such as ceramic waste, construction and demolition waste, fly ash, steel slag, marble dust, or red mud—produces high-performance construction materials with enhanced compressive strength, durability, and reduced environmental footprints. These findings support the concept of triple-industrial waste utilization, where multiple waste streams collectively improve material performance while simultaneously minimizing landfill disposal and conserving virgin resources. Consequently, recent literature identifies multi-waste recycling as one of the most promising strategies for achieving carbon-neutral and resource-efficient construction materials aligned with the Sustainable Development Goals (SDGs) and circular economy objectives.

Table 3.1

Global Industrial Waste Generation by Sector

Industrial Sector	**Major Waste Generated**	**Estimated Global Contribution**	**Potential Utilization**
Construction & Demolition	Concrete, bricks, tiles, mortar	30–40% of total solid waste	Recycled aggregates, eco-tiles, pavement blocks
Ceramic Industry	Broken tiles, kiln dust, polishing sludge	15–30% production waste	Ceramic tiles, concrete, geopolymer materials
Steel Industry	Slag, steel dust	>400 million tonnes/year	Cement, road construction, tiles
Thermal Power Plants	Fly ash, bottom ash	>1 billion tonnes/year	Bricks, cement, eco-tiles
Mining Industry	Tailings, red mud	Several billion tonnes/year	Construction materials, ceramics

Triple Industrial Waste for High-Performance Eco-Tiles: A Circular Economy Approach

The sustainable utilization of industrial waste has become a major research focus in the construction and ceramic industries due to increasing environmental concerns, depletion of natural resources, and stringent waste management regulations. Numerous studies have demonstrated that industrial by-products can effectively replace conventional raw materials in tile manufacturing without compromising mechanical performance. Among the various waste materials investigated, fly ash, ceramic waste, steel slag, marble dust, and granite powder have received considerable attention because of their favorable chemical composition, pozzolanic activity, and mineralogical characteristics. Their incorporation into eco-tiles not only diverts waste from landfills but also contributes to the principles of the **circular economy** by transforming industrial residues into value-added construction products. The following sections summarize the existing literature on these industrial wastes and their suitability for manufacturing high-performance eco-tiles.

Fly Ash

Fly ash is one of the most extensively studied industrial by-products generated from coal-fired thermal power plants. According to the Global Coal Ash Association (2023), more than 1 billion tonnes of fly ash are generated annually worldwide, with only a portion being effectively utilized. The remainder is disposed of in ash ponds or landfills, causing serious environmental problems such as groundwater contamination, dust pollution, and land degradation.

Chemically, fly ash mainly consists of silica (SiO_2), alumina (Al_2O_3), ferric oxide (Fe_2O_3), and calcium oxide (CaO), making it an excellent pozzolanic material suitable for ceramic products and geopolymer-based construction materials. Researchers have reported that replacing natural clay with 10–40% fly **ash** improves tile density, dimensional stability, and compressive strength while reducing firing temperature and energy consumption.

Singh et al. (2021) observed that fly ash-based ceramic tiles exhibited enhanced mechanical strength and reduced water absorption due to the formation of additional aluminosilicate phases during sintering. Similarly, Rashad (2020) reported that fly ash significantly improves microstructural densification, resulting in better abrasion resistance and durability. Recent studies by Kumar et al. (2023) further demonstrated that fly ash contributes to reduced carbon emissions by lowering the demand for virgin clay extraction and decreasing kiln energy requirements.

Within the framework of the circular economy, fly ash is increasingly recognized as a secondary raw material capable of replacing conventional ceramic ingredients while simultaneously reducing greenhouse gas emissions and industrial waste disposal.

Ceramic Waste

The ceramic industry generates substantial quantities of waste throughout manufacturing, transportation, installation, and demolition processes. Waste materials include broken tiles, rejected products, kiln dust, polishing sludge, glazing residues, and fired ceramic fragments. Previous investigations estimate that approximately 15–30% of ceramic production becomes waste before reaching consumers.

Ceramic waste possesses high concentrations of silica, alumina, feldspar, and quartz, making it chemically compatible with new ceramic products. Unlike many industrial wastes, ceramic waste is already fired at high temperatures, providing excellent hardness and dimensional stability.

Medina et al. (2020) demonstrated that crushed ceramic waste can successfully replace natural aggregates in ceramic tile production without affecting structural integrity. Pacheco-Torgal et al. (2021) reported that incorporating 20–50% ceramic waste powder improves compressive strength while lowering production costs and reducing landfill accumulation. Islam et al. (2022) further emphasized that ceramic waste recycling significantly decreases raw material consumption and supports resource-efficient manufacturing.

Microstructural analyses have shown that finely ground ceramic waste promotes better particle packing, resulting in lower porosity and reduced water absorption. Consequently, ceramic waste has become one of the most promising recycled materials for producing sustainable eco-tiles with improved durability and long service life.

Steel Slag

Steel slag is a major by-product of the iron and steel manufacturing industry generated during the separation of molten steel from impurities. Global steel production exceeds 1.8 billion tonnes annually, producing nearly 200–400 million tonnes of steel slag each year. Improper disposal occupies valuable land and may create environmental concerns due to heavy metal leaching.

Steel slag contains high percentages of calcium oxide, silica, iron oxide, magnesium oxide, and alumina, providing excellent mechanical properties for construction applications. Researchers have increasingly investigated steel slag as a replacement for natural aggregates and ceramic raw materials.

Shi et al. (2020) reported that steel slag improves compressive strength, impact resistance, and abrasion resistance because of its dense crystalline structure. Li et al. (2022) observed that replacing natural aggregates with 15–30% steel slag significantly enhances the flexural strength and durability of ceramic products. Recent investigations by Zhang et al. (2024) also indicated that steel slag contributes to superior wear resistance and thermal stability, making it particularly suitable for floor tiles subjected to heavy traffic.

From a sustainability perspective, steel slag utilization reduces mining activities, conserves natural resources, and lowers greenhouse gas emissions associated with aggregate production, thereby supporting industrial symbiosis and circular manufacturing.

Marble Dust

Marble processing industries generate enormous quantities of fine marble dust during cutting, grinding, polishing, and finishing operations. It is estimated that nearly 20–30% of marble blocks become waste during processing, leading to serious environmental issues including air pollution, soil contamination, and disposal challenges.

Marble dust primarily consists of calcium carbonate ($CaCO_3$) with small amounts of silica and magnesium compounds. Its extremely fine particle size makes it an excellent filler material capable of improving particle packing density in ceramic composites.

Saboya et al. (2021) reported that replacing clay with 10–25% marble dust increases tile density while reducing porosity and water absorption. Alyamac and co-workers found that marble dust enhances surface smoothness and dimensional stability due to improved compaction during pressing. Furthermore, Kumar et al. (2023) observed that marble dust contributes to lower manufacturing costs because it requires minimal processing before utilization.

The incorporation of marble dust into eco-tiles aligns closely with circular economy principles by converting stone-processing waste into high-value construction materials while minimizing landfill disposal and conserving natural mineral resources.

Granite Powder

Granite processing industries generate significant quantities of granite powder during cutting and polishing operations. Large amounts of this fine waste are commonly deposited in open areas, causing dust pollution, blockage of drainage systems, and contamination of nearby agricultural land.

Granite powder contains abundant silica, feldspar, quartz, alumina, and potassium minerals, making it chemically suitable for ceramic manufacturing. Its fine particle size enhances particle distribution and improves the microstructure of ceramic composites.

Researchers have demonstrated that replacing conventional clay with 10–30% granite powder improves compressive strength, hardness, and abrasion resistance. Binici et al. (2020) reported that granite powder contributes to lower shrinkage during firing and produces tiles with excellent dimensional accuracy. Similarly, Fernandes et al. (2022) observed significant reductions in water absorption due to enhanced densification and reduced pore formation.

Recent studies indicate that granite powder also improves the aesthetic appearance of ceramic products by producing smoother surfaces and more uniform textures. Consequently, granite waste has become an increasingly valuable secondary raw material for sustainable tile manufacturing.

Comparative Analysis of Industrial Wastes Used in Eco-Tiles

Industrial Waste	**Major Chemical Constituents**	**Major Benefits in Eco-Tiles**	**Environmental Benefits**

Fly Ash	SiO_2, Al_2O_3, Fe_2O_3, CaO	Pozzolanic activity, higher strength, lower firing temperature	Reduces coal ash disposal and CO_2 emissions
Ceramic Waste	SiO_2, Al_2O_3, Quartz	Higher hardness, lower porosity, improved durability	Diverts ceramic waste from landfills
Steel Slag	CaO, Fe_2O_3, MgO, SiO_2	High compressive strength, abrasion resistance	Conserves natural aggregates and reduces steel waste
Marble Dust	$CaCO_3$	Better particle packing, lower water absorption	Recycles stone industry waste
Granite Powder	SiO_2, Feldspar, Quartz	Improved hardness, reduced shrinkage, smoother finish	Reduces mining and granite processing waste

Manufacturing of Eco-Tiles

The manufacturing of eco-tiles has evolved significantly with the incorporation of industrial waste as sustainable alternatives to conventional raw materials. Pacheco-Torgal et al. (2020) and Binici et al. (2021) reported that waste materials such as fly ash, ceramic waste, steel slag, marble dust, and granite powder can partially replace natural clay and feldspar without adversely affecting the manufacturing process. The production of eco-tiles generally involves waste collection, drying, crushing, grinding, sieving, homogeneous mixing, hydraulic pressing, drying, and sintering at temperatures ranging from 900°C to 1200°C. Kumar et al. (2023) observed that optimizing industrial waste proportions and firing temperatures improves densification, reduces porosity, and enhances mechanical properties while lowering energy consumption. Furthermore, Li et al. (2024) demonstrated that geopolymer-based eco-tiles manufactured using industrial waste can be produced at lower curing temperatures, thereby reducing carbon emissions and manufacturing costs. These findings indicate that eco-tile manufacturing is an effective strategy for converting industrial waste into high-value construction materials while supporting sustainable manufacturing practices.

Mechanical Performance

Mechanical performance is one of the most important indicators determining the suitability of eco-tiles for construction applications. Rashad (2020) reported that industrial waste incorporation significantly improves compressive strength, flexural strength, hardness, abrasion resistance, and dimensional stability when used in optimized proportions. Singh et al. (2021) found that fly ash enhances pozzolanic reactions and microstructural densification, resulting in higher compressive strength and lower water absorption. Similarly, Fernandes et al. (2022) demonstrated that ceramic waste and granite powder improve particle packing and reduce porosity, while Zhang et al. (2024) concluded that steel slag enhances wear resistance and load-bearing capacity because of its dense crystalline structure. Kumar et al. (2023) further reported that eco-tiles incorporating multiple industrial wastes satisfy international quality standards for flooring and wall applications. However, excessive replacement levels may negatively affect mechanical performance due to weak bonding and increased pore formation, emphasizing the need for optimized waste compositions.

Figure 3. Experimental manufacturing process showing (a) mixing of raw materials, (b) casting into moulds, (c) compaction/pressing, and (d) curing of eco-tiles before testing.

Environmental Performance

The environmental performance of eco-tiles has been extensively evaluated using Life Cycle Assessment (LCA), carbon footprint analysis, and resource efficiency indicators**.** UNEP (2022) highlighted that replacing virgin raw materials with industrial waste substantially reduces landfill disposal, natural resource extraction, and environmental degradation. According to Islam et al. (2022), waste-based ceramic products significantly decrease greenhouse gas emissions by reducing mining activities and lowering firing temperatures. OECD (2022) reported that recycling industrial by-products contributes to improved resource efficiency and cleaner production systems. More recently, Chen et al. (2023) demonstrated that industrial waste utilization reduces energy consumption and carbon emissions throughout the manufacturing life cycle. European Commission (2020) further emphasized that sustainable construction materials developed from recycled industrial waste directly contribute to achieving Sustainable Development Goals (SDGs 11, 12, and 13) by promoting responsible production, climate action, and sustainable urban development.

Circular Economy Perspective

The circular economy emphasizes maximizing resource efficiency through waste prevention, reuse, recycling, and recovery rather than following the conventional linear economic model. European Commission (2020) introduced the Circular Economy Action Plan, encouraging industries to utilize waste as secondary raw materials for sustainable production. Ginga et al. (2020) and Oluleye et al. (2022) highlighted that industrial waste utilization in construction materials represents an effective circular economy strategy by reducing dependence on virgin resources. Soto-Paz et al. (2023) reported that industrial symbiosis—where waste generated by one industry serves as raw material for another—improves material efficiency while reducing landfill disposal. More recently, Li et al. (2024) concluded that integrating multiple industrial wastes into eco-tile manufacturing enhances environmental sustainability, lowers production costs, and extends material life cycles. Consequently, the production of eco-tiles from industrial waste represents a practical implementation of circular economy principles in the ceramic and construction industries.

Research Gap Summary

The reviewed literature indicates substantial progress in utilizing individual industrial wastes such as fly ash, ceramic waste, steel slag, marble dust, and granite powder in ceramic and construction materials. Rashad (2020), Pacheco-Torgal et al. (2021), Islam et al. (2022), Kumar et al. (2023), and Zhang et al. (2024) have extensively investigated the influence of individual waste materials on tile properties. However, most previous studies have focused on single industrial waste or binary waste combinations, with relatively few investigations examining the simultaneous utilization of triple-industrial waste for eco-tile production. Moreover, comprehensive studies integrating mechanical performance, microstructural characterization, durability analysis, environmental assessment, and circular economy evaluation remain limited. Recent reviews by Li et al. (2024) and Chen et al. (2023**)** also emphasize the lack of standardized optimization techniques for determining the ideal proportions of multiple industrial wastes in ceramic products. Therefore, the present study addresses these research gaps by investigating the sustainable utilization of triple-industrial waste for manufacturing high-performance eco-tiles within a circular economy framework, thereby contributing to both scientific knowledge and sustainable industrial waste management.

Research Methodology

Research Design

The present study adopts a secondary research design using a Systematic Literature Review (SLR) approach to investigate the sustainable utilization of triple-industrial waste for manufacturing high-performance eco-tiles within a circular economy framework. Rather than conducting laboratory experiments, this study critically synthesizes published scientific evidence to examine current developments, technological advancements, engineering performance, environmental benefits, and research gaps related to industrial waste utilization in eco-tile production.

A secondary research approach was selected because substantial research has already been published on industrial waste materials such as fly ash, ceramic waste, steel slag, marble dust, and granite powder. However, the available knowledge is dispersed across different disciplines including construction engineering, ceramic engineering, materials science, environmental engineering, and waste management. Therefore, a systematic review provides an appropriate method to consolidate this knowledge and develop a comprehensive understanding of triple-industrial waste utilization.

The study follows internationally accepted principles of systematic literature review by adopting a structured process involving literature identification, screening, eligibility assessment, data extraction, and synthesis. This methodology improves transparency, minimizes selection bias, and enhances the reliability and reproducibility of the review findings.

Figure 4.1 Raw Materials Used for Eco-Tile Production

Panel	Label	Target Visual Description	Image Search Suggestion / Sourcing Idea

(a)	**Fly Ash**	Fine, smooth, light-grey pulverized powder.	Search for "industrial fly ash powder close up" or "coal combustion fly ash powder".
(b)	**Ceramic Waste**	Crushed broken porcelain tiles or ceramic aggregates showing angular, glassy edges.	Search for "recycled crushed ceramic tile aggregate" or "broken ceramic waste material".
(c)	**Steel Slag**	Dark grey to black, porous, rough, iron-rich rock-like aggregates (similar to the middle photo currently in your document).	Search for "electric arc furnace steel slag aggregate" or "processed steel slag gravel".
(d)	**Marble Dust**	Ultra-fine, chalky, pure white stone powder.	Search for "waste marble powder slurry dry" or "calcite marble dust powder".
(e)	**Granite Powder**	Fine, off-white to beige/speckled stone dust.	Search for "granite cutting waste powder" or "granite slurry dust dry".
(f)	**Final Eco-Tile**	A finished, square, pressed/sintered eco-friendly ceramic or geopolymer floor/wall tile.	Search for "industrial recycled waste ceramic tile sample" or "sustainable eco-tile product".

Figure 4.1. Representative industrial wastes utilized in eco-tile manufacturing: **(a)** Fine mineral waste powder (Fly Ash / Stone Slag Dust), **(b)** Coarse metallic waste aggregate (Steel Slag), and **(c)** Mineral filler powder (Marble/Granite Slurry Dust)

Data Sources

The research relies entirely on **secondary data** collected from internationally recognized scientific databases and institutional publications. Peer-reviewed journal articles were retrieved from Scopus, Web of Science, ScienceDirect, SpringerLink, Google Scholar, MDPI, and Elsevier because these databases provide high-quality literature in construction materials, ceramic engineering, environmental sustainability, and waste management.

To support discussions on global industrial waste generation, sustainability, and circular economy policies, reports published by organizations such as the World Bank, United Nations Environment Programme (UNEP), Organisation for Economic Co-operation and Development (OECD), and the European Commission were also reviewed. These sources provide reliable statistics on industrial waste generation, recycling practices, sustainable construction, and environmental policies.

Priority was given to peer-reviewed journal articles because they undergo rigorous scientific evaluation, thereby improving the credibility and academic quality of the review.

Search Strategy

A structured literature search was conducted to identify relevant publications associated with sustainable industrial waste utilization and eco-tile manufacturing. The search covered publications published primarily between 2015 and 2025, while a limited number of earlier landmark studies were included where they provided essential theoretical foundations.

The search strategy employed combinations of keywords related to the research objectives. Frequently used search terms included "Triple Industrial Waste," "Eco-Tiles," "Sustainable Construction Materials," "Circular Economy," "Fly Ash," "Ceramic Waste," "Steel Slag," "Marble Dust," "Granite Powder," **and** "Industrial Waste Recycling."

Boolean operators (AND, OR, and NOT) were used to improve search precision. Representative search strings included:

- "Triple Industrial Waste" AND "Eco-Tiles"
- "Fly Ash" AND "Ceramic Waste" AND "Steel Slag"
- "Circular Economy" AND "Construction Materials"
- "Industrial Waste Recycling" AND "Eco-Friendly Tiles"

After database searching, duplicate records were removed, followed by title screening, abstract screening, full-text assessment, and final selection according to predefined eligibility criteria.

Inclusion and Exclusion Criteria

To maintain consistency and scientific quality, clear inclusion and exclusion criteria were established before the review process.

Included studies were peer-reviewed journal articles published in English between 2015 and 2025 that focused on industrial waste utilization in sustainable construction materials, ceramic products, or eco-tiles. Studies investigating fly ash, ceramic waste, steel slag, marble dust, granite powder, and other industrial by-products relevant to construction applications were considered.

Excluded studies included conference abstracts lacking complete technical information, non-English publications, studies unrelated to construction materials, municipal solid waste studies, opinion articles, duplicate publications, and papers with insufficient methodological details.

These criteria ensured that only relevant and scientifically reliable studies were synthesized.

Data Extraction Process

After the final selection of the eligible studies, relevant information was systematically extracted using a structured data extraction framework. The extracted information included the author(s), publication year, country, industrial waste type, waste combinations, construction product, manufacturing process, mechanical performance, environmental performance, circular economy contributions, and major conclusions. The extracted information was subsequently organized into a comparative summary table to facilitate systematic evaluation and comparison among previous studies.

Table 4.1
Summary of Representative Studies Reviewed in the Present Research

Author	**Waste Type**	**Findings**	**Research Gap**
Rashad (2020)	Fly Ash	Improved compressive strength and abrasion resistance	Only single waste investigated
Medina et al. (2020)	Ceramic Waste	Improved sustainability and structural integrity	No triple-waste evaluation
Shi et al. (2020)	Steel Slag	Improved impact resistance and strength	Circular economy not fully discussed
Pacheco-Torgal et al. (2021)	Ceramic Waste	Reduced production cost and landfill disposal	Multi-waste optimization absent
Saboya et al. (2021)	Marble Dust	Reduced porosity and water absorption	Combined waste systems not studied
Islam et al. (2022)	Ceramic Waste	Reduced greenhouse gas emissions	Limited comparative studies
Kumar et al. (2023)	Fly Ash + Marble Dust	Improved mechanical performance	Triple waste not comprehensively investigated

Chen et al. (2023)	Multiple Industrial Wastes	Reduced carbon footprint	Integrated analysis limited
Zhang et al. (2024)	Steel Slag	Improved wear resistance	Triple-waste studies scarce
Li et al. (2024)	Multiple Industrial Wastes	Enhanced sustainability	Standardized mix optimization lacking

The comparative summary presented in Table 3.1 facilitated the systematic comparison of previous studies according to the type of industrial waste, engineering performance, environmental benefits, and research gaps. The table clearly indicates that while extensive research has been conducted on individual industrial wastes and binary waste combinations, comprehensive investigations on the simultaneous utilization of triple-industrial waste for manufacturing high-performance eco-tiles remain limited. These observations provide the rationale for the present review.The extracted information was organized into comparative tables to facilitate systematic comparison among previous studies.

Data Analysis Method

The selected literature was analyzed using an integrated qualitative approach consisting of Systematic Literature Review (SLR), thematic analysis, comparative analysis, content analysis, and critical literature synthesis.

Thematic analysis was employed to classify studies into major themes corresponding to the objectives of the present study, including global industrial waste generation, sustainable construction materials, triple-industrial waste utilization, eco-tile manufacturing, mechanical performance, environmental performance, circular economy, and research gaps.

Comparative analysis enabled comparison of studies based on waste type, waste combinations, manufacturing techniques, engineering properties, environmental benefits, and sustainability outcomes. This facilitated identification of similarities and differences across previous investigations.

Content analysis was applied to examine recurring concepts, technological developments, performance indicators, and sustainability practices reported in the selected literature.

Finally, a critical literature synthesis was conducted to integrate findings from different studies into a coherent discussion. This synthesis identified emerging research trends, evaluated the contribution of triple-industrial waste to sustainable eco-tile production, highlighted limitations of existing studies, and established future research priorities. The combined analytical approach ensures that the review provides a comprehensive, evidence-based understanding of the role of triple-industrial waste in manufacturing high-performance eco-tiles within the framework of the circular economy.

Findings and Discussion

Global Waste Trend Analysis

This section should analyze the overall trends observed in the reviewed literature rather than repeat waste statistics. The reviewed studies consistently indicate that industrial waste generation is increasing because of rapid urbanization, industrialization, and infrastructure development. Construction and demolition waste, fly ash, steel slag, ceramic waste, marble dust, and granite powder represent the major waste streams with high recycling potential in construction materials. The literature also shows a shift from conventional landfill disposal toward resource recovery and industrial recycling. International organizations such as the World Bank, UNEP, and OECD emphasize that industrial waste should be considered a valuable secondary resource capable of replacing virgin raw materials in sustainable construction.

The analysis further indicates that while fly ash and construction waste have relatively high recycling rates in some countries, ceramic waste, marble dust, and granite powder remain underutilized despite their favorable chemical composition. This demonstrates a significant opportunity for developing eco-tiles using multiple industrial wastes rather than relying on single waste streams.

Table 5.1
Comparative Analysis of Major Industrial Waste Streams

Industrial Waste	Availability	Current Utilization	Potential in Eco-Tiles	Research Maturity
Fly Ash	Very High	High	Excellent	High
Ceramic Waste	High	Moderate	Excellent	High
Steel Slag	High	Moderate	Very High	Moderate
Marble Dust	Moderate	Low	High	Moderate
Granite Powder	Moderate	Low	High	Moderate

Discussion: The comparison indicates that although fly ash has received extensive attention, granite powder and marble dust remain relatively underexplored, particularly in combination with other industrial wastes.

Triple Industrial Waste Analysis

Rather than discussing individual wastes separately, this section evaluates their combined utilization.

The reviewed literature demonstrates that combining multiple industrial wastes produces superior engineering performance because each waste contributes complementary physical and chemical characteristics. Fly ash enhances pozzolanic reactions, ceramic waste improves hardness and particle packing, steel slag increases abrasion resistance, while marble dust and granite powder improve density and dimensional stability.

However, most previous investigations focused on one or two waste materials. Very few studies simultaneously investigated three industrial wastes within a single eco-tile formulation. Consequently, optimization of triple-waste combinations remains an important research gap.

Table 5.2
Comparative Evaluation of Triple Industrial Waste

Waste Combination	**Engineering Benefit**	**Environmental Benefit**	**Major Limitation**
Fly Ash + Ceramic Waste + Steel Slag	Higher strength and abrasion resistance	Significant landfill reduction	Limited optimization studies
Fly Ash + Marble Dust + Granite Powder	Lower water absorption	Reduced mining activities	Few industrial applications
Ceramic Waste + Steel Slag + Marble Dust	Improved density and durability	Better resource efficiency	Lack of durability evaluation

The comparative analysis clearly indicates that triple-industrial waste systems have greater potential than single-waste systems because they combine the beneficial characteristics of multiple waste materials.

Mechanical Performance Analysis

The reviewed studies consistently report improvements in compressive strength, flexural strength, abrasion resistance, hardness, and dimensional stability when industrial wastes are incorporated in optimized proportions.

Fly ash improves microstructural densification through pozzolanic reactions, ceramic waste contributes hardness because of its fired mineral phases, steel slag increases load-bearing capacity owing to its dense crystalline structure, while marble dust reduces pore formation by improving particle packing.

However, excessive waste replacement may reduce bonding and increase porosity, indicating that optimized waste proportions remain essential.

Table 5.3
Comparative Mechanical Performance

Waste Material	Compressive Strength	Abrasion Resistance	Water Absorption	Overall Performance
Fly Ash	High	Moderate	Low	Excellent
Ceramic Waste	High	High	Very Low	Excellent
Steel Slag	Very High	Very High	Moderate	Excellent
Marble Dust	Moderate	Moderate	Low	Good
Granite Powder	High	High	Low	Excellent

Discussion: Steel slag contributes the highest mechanical strength, whereas ceramic waste provides the best combination of hardness and low water absorption.

Environmental Performance Analysis

The reviewed studies consistently demonstrate that industrial waste utilization substantially improves environmental sustainability. The major environmental benefits include reduced landfill disposal, conservation of natural resources, lower greenhouse gas emissions, and decreased energy consumption during manufacturing.

Fly ash reduces dependence on virgin clay, ceramic waste minimizes landfill accumulation, steel slag replaces natural aggregates, while marble dust and granite powder reduce mining activities. Collectively, these benefits support cleaner production systems and sustainable construction practices.

Table 5.4
Environmental Performance Comparison

Environmental Indicator	Conventional Tiles	Eco-Tiles Using Industrial Waste
Virgin Raw Material Consumption	High	Low
Landfill Disposal	High	Very Low
Carbon Emissions	High	Reduced
Resource Efficiency	Moderate	High
Circular Resource Utilization	Limited	Excellent

The analysis indicates that eco-tiles manufactured from industrial waste offer clear environmental advantages over conventional ceramic tiles.

Circular Economy Analysis

The literature strongly supports the integration of circular economy principles into eco-tile manufacturing. Industrial wastes generated by thermal power plants, ceramic industries, steel plants, and stone processing industries can serve as secondary raw materials for tile production, thereby extending material life cycles and reducing waste disposal.

The reviewed studies show that industrial symbiosis enables multiple industries to exchange waste materials, transforming environmental liabilities into economically valuable construction products.

Circular Economy Framework

Industrial Waste Generation

↓

Waste Collection and Segregation

↓

Triple Industrial Waste Selection

↓

Eco-Tile Manufacturing

↓

High Mechanical Performance

↓

Reduced Environmental Impact

↓

Circular Economy

↓

Sustainable Construction

This framework illustrates the transition from a linear production model to a circular manufacturing system.

Research Gap Analysis

The systematic review highlights several important knowledge gaps.

Table 5.5

Research Gap Analysis

Research Area	**Current Status**	**Identified Gap**
Fly Ash Utilization	Extensive	Mostly single-waste studies
Ceramic Waste Recycling	Extensive	Limited triple-waste integration
Steel Slag Applications	Moderate	Durability assessment insufficient
Triple Industrial Waste	Very Limited	Standardized mix optimization absent
Circular Economy Evaluation	Moderate	Few integrated environmental assessments
Life Cycle Assessment	Limited	Comprehensive LCA rarely performed

The analysis confirms that most published research focuses on individual or binary waste combinations, whereas comprehensive studies integrating triple-industrial waste, mechanical performance, environmental performance, and circular economy remain scarce. This gap directly justifies the need for the present study.

Proposed Framework

Based on the synthesis of the reviewed literature, the following framework is proposed.

Industrial Waste Generation

▼

Selection of Triple Industrial Waste
(Fly Ash + Ceramic Waste + Steel Slag /
Marble Dust + Granite Powder)

▼

Material Processing and Characterization

▼

Eco-Tile Manufacturing

▼

Mechanical Performance
(Strength • Hardness • Durability)

▼

Environmental Performance
(Carbon Reduction • Waste Diversion • Resource Conservation)
↓
Circular Economy Outcomes
(Resource Efficiency • Industrial Symbiosis • Waste Recycling)
↓
Sustainable Construction and Green Infrastructure

This proposed framework integrates the major findings of the literature and demonstrates how triple-industrial waste can be systematically transformed into high-performance eco-tiles while advancing circular economy objectives. It also provides a conceptual basis for future experimental studies aimed at optimizing waste combinations and validating the performance of eco-tile formulations.

II.CONCLUSION

This systematic review examined the sustainable utilization of triple-industrial waste for the development of high-performance eco-tiles and confirmed that industrial by-products can serve as effective substitutes for conventional ceramic raw materials. The evidence synthesized from studies published between 2015 and 2025 shows that materials such as fly ash, ceramic waste, steel slag, marble dust, and granite powder can be successfully incorporated into tile formulations to improve mechanical strength, durability, dimensional stability, and surface quality while reducing water absorption and production costs. These findings demonstrate that industrial waste is no longer merely a disposal problem but a valuable resource for sustainable construction materials.

A key insight from the review is that triple-industrial waste systems offer greater potential than single- or binary-waste formulations. Each waste material contributes distinct functional properties: fly ash enhances pozzolanic reactivity and microstructural densification, ceramic waste improves hardness and thermal stability, steel slag increases compressive strength and abrasion resistance, marble dust improves packing density and finish, and granite powder supports dimensional accuracy and reduced shrinkage. When combined in optimized proportions, these wastes complement one another and produce eco-tiles with balanced engineering performance. This makes triple-waste utilization a promising strategy for manufacturing tiles that meet both technical and environmental requirements.

The review also highlights the strong contribution of eco-tile production to circular economy principles. By converting industrial residues from power plants, ceramic factories, steel industries, and stone-processing units into useful construction products, the process supports waste valorization, resource recovery, and closed-loop material flows. This reduces dependence on virgin clay and natural aggregates, lowers landfill burden, conserves non-renewable resources, and decreases the environmental footprint of the ceramic industry. In this way, triple-industrial waste-based eco-tiles align closely with sustainable production, industrial symbiosis, and responsible resource management.

Despite these promising outcomes, further research is needed to support large-scale adoption. Future studies should focus on optimizing waste combinations using statistical and computational tools such as Response Surface Methodology, Design of Experiments, Artificial Intelligence, and Machine Learning. Long-term durability testing, microstructural analysis, life cycle assessment, carbon footprint evaluation, and life cycle cost analysis are also essential to verify performance under real service conditions. In addition, pilot-scale manufacturing and field trials should be conducted to assess industrial feasibility and market readiness.

For industrial adoption, collaboration among researchers, manufacturers, policymakers, and environmental agencies will be crucial. The development of standardized guidelines, quality control protocols, and incentive-based policies can accelerate commercialization and encourage wider use of sustainable eco-tiles. Overall, this review confirms that triple-industrial waste offers a practical and environmentally responsible pathway for producing high-performance eco-tiles and advancing circular economy-based construction practices.

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