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Review article

# Volcanic rocks in the 21st century: Multifaceted applications for sustainable development

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A B S T R A C T

Volcanic rocks, with their diverse physicochemical properties, are pivotal in numerous scientific and industrial applications. This review comprehensively examines the multifaceted uses of volcanic rocks, focusing on their roles in sustainable construction, environmental remediation, and industrial catalysis. Volcanic materials like basalt and pumice enhance the durability and thermal efficiency of construction materials, while their porous structures facilitate the adsorption of pollutants in environmental applications. Additionally, their catalytic properties are harnessed in various industrial processes, promoting cleaner production techniques. This review synthesizes current research and explores future innovations, emphasizing the potential of volcanic rocks to contribute to sustainable development and technological advancement. The integration of volcanic rocks in sustainable practices highlights their role in promoting ecological balance and resource efficiency. The findings underscore the significance of interdisciplinary approaches in leveraging volcanic rocks for eco-friendly and economically viable solutions, demonstrating their potential to address global challenges through innovative applications and future research directions.

## 1. Introduction

Volcanic rocks, formed through the solidification of magma during volcanic activity, possess a broad spectrum of physicochemical properties, making them crucial for various scientific and industrial applications [1–8]. These rocks, with their diverse mineral compositions and unique physical characteristics such as high strength, thermal stability, and chemical durability, have gained significant attention in materials science [9–14]. Notably, basalt [15–17], pumice [18,19], andesite [20,21], rhyolite [22,23], obsidian [24,25], scoria [26–28], and volcanic ash [29,30] exhibit outstanding properties that not only make them valuable for academic research but also present significant opportunities for technological advancements. The relative abundance and widespread distribution of these materials make them attractive as sustainable resources, especially in the context of global efforts to reduce environmental impact and promote sustainability.

Fig. 1(a) demonstrates a consistent upward trajectory in the number of publications on volcanic rocks between 2000 and 2024, punctuated by pronounced peaks in 2021 and 2022. This trend underscores the increasing global attention to the study of volcanic materials, driven by advancements in geoscientific tools, interdisciplinary research initiatives, and the expanding recognition of volcanic rocks' multifaceted roles in construction, environmental management, and industrial applications. The significant growth in recent years can also be linked to the development of high-resolution analytical technologies and an enhanced understanding of volcanic processes, enabling more comprehensive investigations. Fig. 1(b) presents the geographic distribution of publications, with the United States leading, followed closely by China. These two nations account for the largest share of research outputs, reflecting their substantial investments in geoscience infrastructure and strategic interest in sustainable and innovative applications of volcanic materials. The United Kingdom, Germany, and Japan also feature prominently, showcasing their academic strengths and technological expertise in Earth sciences. Countries such as Italy, Australia, and Canada further highlight the global scope of volcanic rock research, albeit with varied focus areas and resource allocations. This disparity in publication output reflects differences in national research priorities, funding availability, and access to volcanic regions, underscoring the uneven distribution of geoscience research capacities worldwide.

The application of volcanic rocks spans several critical fields, with particularly notable impacts in construction, environmental remediation, and resource recovery. In the construction sector, volcanic rocks have emerged as essential materials in the development of sustainable and energy-efficient building solutions [31,32]. Basalt fibers, derived from volcanic basalt, are recognized for their exceptional mechanical strength, heat resistance, and corrosion resistance [33,34]. These fibers

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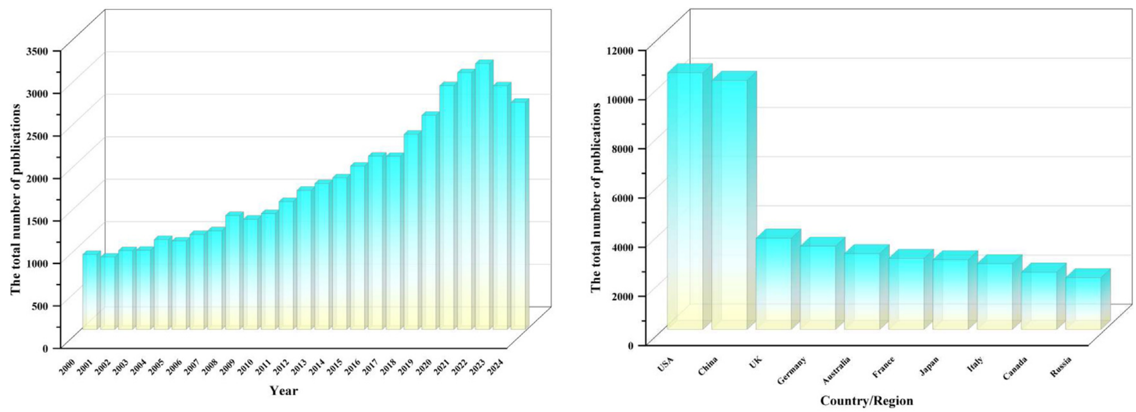


(a) (b)

**Fig. 1.** Statistic chart based on Web of Science Core Collection database by searching the keywords. 'volcanic rock/volcanic ash/volcanic tuff/basalt/andesite/rhyolite/obsidian/pumice/scoria':
(a) numbers of published articles from 2000 to 2024; (b) numbers of published articles from different country/region (TOP 10).

are integrated into composite materials used in high-performance sectors, including aerospace, military, and civil engineering, enhancing the durability and structural integrity of various constructions [35–38]. Moreover, volcanic ash and pumice, with their pozzolanic properties, are increasingly used in the production of eco-friendly concrete and cement [39–41]. These materials significantly improve the performance of concrete, enhancing its compressive strength, reducing its weight, and increasing its durability, while also contributing to the reduction of carbon emissions during production [42,43]. As a result, volcanic rocks play a key role in advancing sustainable building practices, particularly in low-carbon construction and green infrastructure projects. In addition, volcanic rocks have proven effective in environmental applications, such as pollution control and remediation [44,45]. Their high surface area and porous structure make them excellent adsorbents for pollutants, including heavy metals, organic contaminants, and other toxic substances in water and soil [46,47]. These materials are used in water treatment processes, enhancing filtration efficiency and improving water quality [48–50]. Furthermore, the catalytic properties of certain volcanic rocks are harnessed in advanced oxidation processes to degrade persistent pollutants [51,52]. As environmental degradation continues to rise, the role of volcanic rocks in providing sustainable solutions for pollution control and ecological restoration is expected to expand.

This review aims to provide a comprehensive analysis of the current state of research on volcanic rocks, focusing on their multifaceted applications and potential contributions to sustainable development. The paper synthesizes findings from various fields, including construction, environmental remediation, and resource management, to explore the ways in which volcanic rocks can enhance material performance, improve resource efficiency, and reduce environmental footprints. Furthermore, this review will address the emerging trends in volcanic rock research, including the development of innovative volcanic rock-based products and technologies. By evaluating the challenges and opportunities in their applications, this review seeks to offer a holistic view of how volcanic rocks can contribute to sustainable practices in both industrial and environmental contexts. Finally, the review will propose future directions for research, particularly in areas such as circular economy, renewable energy, and green infrastructure, where volcanic rocks could play a transformative role in shaping a more sustainable future.

## 2. Methodology

For this comprehensive review on the applications and advancements of volcanic rocks across multiple sectors, a thorough literature search was conducted using several scientific databases, including Web of Science, ScienceDirect, Google Scholar, and CNKI. The search strategy was carefully designed to cover an extensive range of keywords pertinent to the study's focus. The primary keyword, "volcanic rocks", was combined with secondary keywords related to specific applications such as "catalysis", "construction materials", "environmental remediation", "agriculture", "cosmetics", "personal care", "cultural heritage", "artistic uses", "phytoremediation", and "water treatment".

Additional keywords were incorporated to capture various properties and technologies associated with volcanic rocks, including "thermal insulation", "acoustic insulation", "adsorption", "mechanical properties", "porosity", "surface treatment", "mineral composition", "geomechanical properties", and "thermal stability". The search also included terms related to specific industrial uses like "filtration media", "catalyst supports", "soil amendments", "building materials", "permeable pavements", "lightweight aggregates", and "geopolymers". To ensure the inclusion of the latest innovations and trends, keywords such as "sustainable development", "green technologies", "environmental impact", "circular economy", "carbon sequestration", "renewable energy", and "waste management" were also used.

A stringent data filtration strategy was employed to ensure the relevance and quality of the selected publications. Emphasis was placed on including literature that directly pertains to the practical applications and technological advancements of volcanic rocks. Studies primarily focused on unrelated geological aspects or that only tangentially mentioned volcanic rocks without concrete applications were systematically excluded. This careful selection process was aimed at pinpointing the most relevant and impactful research, closely aligning with the study's scope and objectives, which include mapping the current landscape and identifying future directions in the use of volcanic rocks.

## 3. Characteristics and extraction of volcanic rocks

Volcanic rocks are formed when magma extrudes onto the Earth's surface, subsequently solidifying as lava. The rapid cooling of lava, influenced by its composition and dissolved gas content, determines the texture and mineralogy of the resultant rocks [53]. For instance, fine-grained textures such as those in obsidian indicate rapid cooling conditions [54]. The classification of volcanic rocks is typically based on their silica content and mineral assemblages. Basalts, with less than 52% silica, are dominated by plagioclase feldspar, pyroxene, and olivine [55], whereas rhyolites, with over 70% silica, comprise quartz, potassium feldspar, and plagioclase [56]. Andesites have intermediate compositions between basalts and rhyolites.

The global distribution of volcanic rocks correlates strongly with specific tectonic settings [57]. Basalts are predominantly found at mid-ocean ridges, where new seafloor is created by upwelling mantle at divergent plate boundaries [58]. In contrast, andesites and rhyolites are commonly associated with subduction zones, where water introduction reduces the mantle wedge's melting point [59]. Mantle plumes also contribute to intraplate volcanism, evident in hotspots like Hawaii [60] and extensive igneous provinces such as the Deccan Traps [61].

The physical properties of volcanic rocks are intrinsically determined by their crystallization conditions. Obsidian, with its fine-grained, vitreous texture, results from rapid cooling near the Earth's surface [62]. Pumice's vesicular and porous nature, caused by gas-rich magmas, highlights differences in density across volcanic rock types [63]. Mechanical properties such as strength and permeability are governed by characteristics like porosity, fracture prevalence, and void space interconnectedness [64]. Chemically, volcanic rocks' diverse mineralogical compositions reflect their magmatic origins and crystallization histories. Silica content is pivotal, with basalts being silica-deficient [65] and rhyolites silica-rich [66]. Trace element abundances and isotopic ratios offer insights into magmas' sources, differentiation processes, and tectonic settings. Chemical interactions, particularly in aqueous conditions, can lead to weathering and alteration, modifying original mineralogical and geochemical signatures [67]. Table 1 provides an overview of main volcanic rocks, detailing their formation processes, characteristics, and unique features.

Table 2 showcases the main extraction and processing methods for volcanic rocks. Historically, volcanic rock extraction relied on rudimentary manual techniques, but technological advancements have led to more sophisticated and large-scale methods. For surface deposits, open-pit operations are commonly employed, systematically removing overburden to reveal underlying formations, which are then extracted using explosives and heavy-duty machinery [68]. For deeper deposits, underground mining techniques, including shaft sinking and tunneling, are adopted. Quarrying techniques enhance precision by facilitating the removal of specific rock slabs or blocks. Remote sensing and Geographic Information System (GIS) technologies have been instrumental in identifying potential sites and streamlining logistical operations [69–71]. Environmental impact assessments are routinely conducted before extraction to address ecological considerations.

## 4. Applications and advancements in volcanic rock research

The utilization of volcanic rocks has expanded significantly, encompassing various innovative applications that leverage their unique physicochemical properties. This comprehensive exploration into the practical and technological uses of volcanic rocks illustrates their critical role in advancing multiple industries. From enhancing soil fertility in agriculture to serving as efficient catalysts in industrial processes, volcanic rocks demonstrate remarkable versatility. Their structural attributes, including porosity, thermal resistance, and mineral richness, enable them to meet the demands of modern engineering, environmental sustainability, and even personal care.

### *4.1. Agriculture*

In agricultural applications, the strategic deployment of volcanic derivatives, particularly pumice and basalt, has been under rigorous scrutiny for their beneficial impact on soil enhancement and sustainable fertility [132,133]. Empirical studies employing water retention curves have elucidated the capacity of these volcanic materials to significantly augment soil moisture levels, a critical factor for plant growth in arid regions [134]. Complementary to this is the slow nutrient release from such amendments, with sequential extraction methods uncovering a steady dissolution of key elements like potassium and phosphorus, pivotal for crop development [135]. This measured liberation contrasts sharply with the rapid depletion often associated with conventional fertilizers, suggesting a potential reduction in nutrient runoff and heightened uptake efficiency by plants.

Ma et al. investigated the effects of biochar and volcanic rock addition on the humification process and microbial communities during aerobic composting of cow manure [136], demonstrating that biochar reduced the E4/E6 value by 10.42% and increased the abundance of *Geobacillus* by 1.69 times, while volcanic rock decreased the E4/E6 value by 11.31% and enhanced the abundance of *Thermobacillus* by 1.29 times and *Paenibacillus* by 1.72 times, thus promoting compost maturity through microbial shifts and metabolic adjustments.

Panhwar et al. investigated the efficacy of ground magnesium limestone and ground basalt, both applied with bio-fertilizer, to sustain rice production on acid sulfate soils in Malaysia [137]. Their results demonstrated that the application of these amendments significantly improved soil fertility, increasing the concentrations of essential nutrients such as Ca, Mg, Zn, and Cu. Notably, the combination of basalt and bio-fertilizer proved to be the most effective treatment, enhancing soil pH and alleviating toxicity from $Al^{3+}$ and $Fe^{2+}$, which ultimately led to a 6 t $ha^{-1}$ increase in rice grain yield during the first season.

Mehlferber et al. investigated the impact of volcanic ash fertilizer containing micronutrients on tomato plants [138], revealing that Azomite supplementation led to a significant increase in fruit production and temporally selective modifications in the rhizosphere and root microbiome, with shifts in microbial functional pathways, particularly in carbohydrate metabolism.

Dida et al. investigated the release and percolation rates of nutrients from regular and obsidian-based slow-release fertilizers [139]. They found that while regular fertilizers released potassium and phosphate almost entirely within seven days, less than 20% of these nutrients were leached from the obsidian-based slow-release fertilizer over the same period. After 30 days, the slow-release fertilizer leached 46% and 50% of potassium and phosphate, respectively, demonstrating a significantly slower release rate compared to regular fertilizers, which leached nutrients 6 to 8 times faster.

Sekiguchi et al. investigated the temperature dependence of volcanic ash soil aggregate stability under different fertilization treatments, revealing that macro-aggregates ($\geq$250 μm) from the organic manure plot were significantly more stable than those from the chemical fertilizer plot [140], with a notable increase in polysaccharide content in the soil suspension, which more than doubled when the temperature was raised from 20 to 80 °C, emphasizing the role of polysaccharides in aggregate stability at elevated temperatures.

Volcanic rock is emerging as a key player in sustainable agriculture, proven to be stable and effective for carbon sequestration through detailed assessments [141,142]. Growth trials juxtaposing volcanic rock-amended soils against control groups have borne witness to marked increments in plant biomass, signifying not only an enhancement in pedological fertility but also a stride towards carbon neutrality in agricultural practices [143]. The confluence of these findings underscores the potential of volcanic rock derivatives to operate as a keystone in the nexus of soil health, crop productivity, and ecological sustainability, meriting further exploration into their long-term field applications and optimal incorporation strategies within diverse agroecosystems.

### *4.2. Industry*

The industrial applications of volcanic rocks have gained notable attention due to their distinctive physical and chemical attributes. These materials, shaped by volcanic activity, are defined by their porous structure, thermal stability, and rich mineral composition. Such characteristics make volcanic rocks exceptionally suited for various industrial uses, including adsorbents, filtration media, and catalysts. The natural properties of volcanic rocks enhance contaminant adsorption, catalyze reactions efficiently, and improve filtration processes. This versatility underlines their potential to tackle environmental issues and promote sustainable industrial practices. As ongoing research unfolds, the integration of volcanic rocks in innovative technological solutions is expected to expand, further driving progress in environmental management and industrial operations.

**Table 1**
Characteristics and types of main volcanic rocks.

| Type | Origin | Texture | Silica content | Key features | Morphology | References |
|---|---|---|---|---|---|---|
| Basalt | Extrusive, from fast-cooling lava | Fine-grained | Low (<52%) | Durable, dark colored |  | [72–78] |
| Andesite | Extrusive, intermediate in silica | Fine to medium-grained | Intermediate (52%–63%) | Medium color, intermediate composition |  | [79–85] |
| Rhyolite | Extrusive, high in silica | Aphanitic | High (>70%) | Light colored, high viscosity |  | [86–90] |
| Obsidian | Extrusive, rapid cooling of felsic lava | Glassy, smooth | High (>70%) | Very smooth, glass-like |  | [91–95] |

(*continued on next page*)

*4.2.1. Adsorbent or filtration media*

In the domain of environmental remediation, volcanic rocks have been increasingly recognized for their efficacy as adsorbent and filtration media. Predominantly, the porous nature and high surface area of these rocks facilitate the adsorption of a wide range of contaminants, making them suitable for water and air purification processes [144–146]. The adsorptive capacity of volcanic rocks is attributed to their intricate pore structures and the presence of various minerals, which enable the trapping and removal of pollutants from aqueous and gaseous phases [147,148]. This characteristic is particularly crucial in the context of industrial effluents and urban wastewater treatment, where the removal of heavy metals, organic compounds, and other toxic substances is imperative.

The utilization of volcanic rocks in filtration systems has been optimized through the selection of specific rock types, each with unique properties suitable for targeting different contaminants. For example, the use of basaltic rocks is prevalent in scenarios requiring the removal of heavy metals due to their high cation exchange capacity [149–151]. On the other hand, pumice and scoria, with their highly vesicular structure, are effective in trapping particulate matter and thus are extensively employed in filtration systems [152–154]. The adaptability of these volcanic rocks to various filtration needs is a testament to their versatility, making them a valuable resource in environmental engineering practices.

In addition to their direct use as filtration media, volcanic rocks serve as a foundation for developing composite materials with enhanced adsorptive properties [155]. Research in this area has led to the creation of hybrid materials that combine volcanic rocks with other adsorbents, such as activated carbon or metal oxides, to augment their pollutant removal efficiency [156,157]. This synergy between volcanic rocks and other materials not only improves the overall performance of the filtration systems but also broadens the scope of their applicability in tackling a diverse array of environmental pollutants [158]. Table 3 summarizes the adsorption capabilities of certain volcanic rock-based

**Table 1** (*continued*).

| Type | Origin | Texture | Silica content | Key features | Morphology | References |
|---|---|---|---|---|---|---|
| Pumice | Extrusive, rapid cooling with gas release | Vesicular, frothy | Variable | Lightweight, high porosity |  | [96–103] |
| Scoria | Extrusive, similar to pumice but denser | Vesicular, porous | Low to intermediate | Darker, heavier than pumice |  | [104–109] |
| Tuff | Extrusive, formed from consolidated ash | Fine-grained to porous | Variable | Light to moderate density, contains ash particles and volcanic glass |  | [110–113] |

Image source for rock and mineral specimens: National Infrastructure of Mineral Rock and Fossil Specimen Resources (http://www.nimrf.net.cn)

**Table 2**
Main extraction methods for volcanic rocks.

| Method/Technique | Description | Tools/Technology used | Advantages | Disadvantages | Environmental Impact | Reference |
|---|---|---|---|---|---|---|
| Open-Pit mining | Removal of surface layers to access rock formations | Excavators, bulldozers, explosives | High yield, efficient | Significant landscape alteration, high cost | High, includes deforestation, habitat destruction | [114–118] |
| Underground mining | Accessing deeper deposits within the Earth's crust | Shaft sinking, tunneling equipment | Access to deep resources | High cost, safety risks | Moderate, localized subsidence, water contamination | [119–124] |
| Quarrying | Precision removal of specific rock slabs or blocks | Wire saws, diamond-tipped tools | High precision, minimal waste | Equipment-intensive | Moderate, managed site impact | [125–131] |

materials for pollutants.

The continuous development and application of volcanic rock-based adsorbents and filtration media underscore the importance of these natural resources in addressing contemporary environmental challenges. Their role in purifying water and air, essential components of a healthy ecosystem, is invaluable. As research progresses, it is anticipated that novel applications and advancements in the modification and utilization of volcanic rocks will emerge, further solidifying their position as a crucial element in sustainable environmental management practices.

#### 4.2.2. Catalysts

In the realm of catalysis, volcanic rocks have emerged as a significant focus of research due to their intrinsic properties which facilitate various chemical reactions. These rocks, often rich in silicates and metal oxides, provide a natural, robust framework for catalytic activities. The structural integrity and thermal stability of volcanic rocks make them suitable catalysts or catalyst supports in a range of industrial processes [183].

Revathi R. Bacsa et al. demonstrated that volcanic stones from Santorini can act as natural catalysts for the growth of carbon nanotubes [184], revealing that synthetic catalysts mimicking these rocks can achieve high selectivity for thin multiwalled carbon nanotubes production. Señorans et al. investigated the use of Ce/Pumice and Ni/Pumice as heterogeneous catalysts for syngas production from biomass gasification [185], finding that these catalysts lower the gasification temperature and increase the gasification rate compared to non-catalytic processes. Valadi et al. synthesized a cellulose/pumice hybrid nanocomposite and demonstrated its efficiency in ultrasound-assisted synthesis of 1,4-dihydropyridine derivatives [186], achieving high reaction yields of up to 97% in just 10 min.

The surface chemistry of volcanic materials plays a pivotal role in their catalytic performance, with the presence of active sites on the

**Table 3**
Adsorption capacity of volcanic rock-based material for pollutants.

| Adsorbent | Target pollutant | Adsorption capacity (mg/g) | Reference |
|---|---|---|---|
| Ferric-impregnated volcanic ash | Arsenic (V) | 6.3 | [159] |
| Nano volcanic ash | Cadmium (II) | 166.6 | [160] |
| Rhyolite tuff powder | Lead (II) | 3.0 | [161] |
| ZIF-8 functionalized basalt fiber felt | Iodine | 3614 | [162] |
| Hybrid multifunctional composite of chitosan and altered basalt | Barium (II) | 116.0 | [163] |
| Volcanic ash-based porous geopolymers | Lead (II) | 312.5 | [164] |
| Polypyrrole decorated volcanics | Sulfamethoxazole | 1427 | [165] |
| $\alpha$-$Fe_2O_3$ nanoparticles-coated volcanic rock | Cadmium (II) | 127.2 | [166] |
| Scoria stone | Phenol | 67.1 | [167] |
| Calcined Lapindo volcanic mud | Methyl orange | 333.3 | [168] |
| $Fe_2O_3$ porous microspheres modified pumice | Phosphate | 1.35 | [169] |
| Marble, pumice, and basalt triple combination | Phosphate | 35.1 | [170] |
| Pumice | Copper (II) | 1.4 | [147] |
| Chitosan–red scoria and chitosan–pumice blends | Arsenic (V) | 0.7 | [171] |
| Natural volcanic tuff | Zinc (II) | 14.7 | [172] |
| Virgin pumice | Cadmium (II) | 0.003 | [173] |
| Pumice | $SO_2$ | 33.4 | [174] |
| Lanthanum oxide nanoparticles modified pumice | Phosphate | 82.7 | [175] |
| CNT loaded Pumice | Ciprofloxacin | 28.6 | [176] |
| Modified of volcanic ash | Malachite green | 170.6 | [177] |
| Nano-scale pumice mine waste | Metronidazole | 15.3 | [178] |
| Pumice | Cs-137 | 471.7 | [179] |
| Pumice | Remazol Red RB | 38.9 | [180] |
| Zeolite synthetized from volcanic ash | Ammonium | 18.4 | [181] |
| Scoria | Sulfate | 10.1 | [182] |

**Table 4**
Catalysis degradation of volcanic rock-based material for pollutants.

| Catalyst | Catalysis method | Target pollutant | Catalysis efficiency | Reference |
|---|---|---|---|---|
| Fe-modified pumice | Ozonation catalysis | *p*-chloronitrobenzene | Removal efficiency: 90.8%; Time: 15 min | [187] |
| $ZrO_2$-pumice | Sono-catalysis | Rifampin | Removal efficiency: 95%; Time: 90 min | [188] |
| ZnO-scoria | Photo-catalysis | Phenazopyridine | Removal efficiency: 72.5%; Time: 4 h | [189] |
| CuO/ZnO-scoria | Photo-catalysis | Blue 113 | Removal efficiency: 62.4%; Time: 4 h | [190] |
| rGO@$MnO_2$- Pumice | Photo-catalysis | Ciprofloxacin | Removal efficiency: 80.0%; Time: 6 h | [191] |
| $CeO_2$/$Bi_2WO_6$- Pumice | Photo-catalysis | Tetracycline | Removal efficiency: 91.7%; Time: 90 min | [192] |
| Cu-modified pumice | $H_2O_2$ catalytic oxidation | Cyanide | Removal efficiency: 95.0%; Time: 24 h | [193] |
| Fe-modified pumice | Catalytic wet peroxide oxidation | Orange II | Removal efficiency: 100%; Time: 4 h | [194] |
| $SnO_2$-pumice | Photo-catalysis | Methyl orange | Removal efficiency: 85.0%; Time: 40 min | [195] |
| ZnO-pumice | Photo-catalysis | Rhodamine B | Removal efficiency: 99.3%; Time: 3 h | [196] |
| Basalt | Photo-Fenton-catalysis | Atrazine | Removal efficiency: 96.0%; Time: 3 h | [197] |
| Silicate -pumice | Ozonation catalysis | Diclofenac | Removal efficiency: 73.3%; Time: 1 h | [198] |
| PDMS-$SiO_2$-chitosan@$TiO_2$-pumice | Photo-catalysis | Methylene blue | Removal efficiency: 36.0%; Time: 30 h | [199] |
| Zinc oxyhydroxide-pumice | Ozonation catalysis | *p*-chloronitrobenzene | Removal efficiency: 93.4%; Time: 20 min | [200] |
| $TiO_2$-Pd nanocomposite immobilized on pumice stone | Sono-photo-catalysis | Ciprofloxacin | Removal efficiency: 79.4%; Time: 120 min | [201] |

surface–whether naturally occurring or engineered through treatments–being essential for the adsorption and subsequent reaction of reactants. The porous structure of certain volcanic rocks, such as pumice and basalt, significantly enhances the surface area available for catalytic reactions, thereby increasing process efficiency [202]. Research has focused on modifying these surfaces to optimize reactivity and selectivity for specific reactions, including the conversion of greenhouse gases into less harmful substances or valuable chemicals [203]. Furthermore, the application of volcanic rocks in photocatalysis represents a promising area of development. Their potential in harnessing solar energy to drive chemical reactions offers an innovative approach to sustainable chemistry [204]. In this context, volcanic rocks are explored for their ability to facilitate the breakdown of organic pollutants in water, thereby contributing to environmental remediation efforts [205]. Table 4 shows the catalytic degradation of volcanic rock-based material for pollutants.

The utilization of volcanic rocks as catalysts and catalyst supports underscores their emerging significance in advancing sustainable industrial practices. Continued research in this field is anticipated to uncover new pathways for enhancing their catalytic properties and broadening their range of applications. This development is expected to contribute significantly to various industries, including energy production, environmental management, and green chemistry, solidifying the role of volcanic rocks in innovative and sustainable technological solutions. This application highlights not only the versatility of volcanic rocks in


**Fig. 2.** Representative buildings incorporating volcanic rocks in construction:
(a) Colosseum; (b) Parthenon; (c) Borobudur; (d) Pompeii; (e) Trulli of Alberobello; (f) Göreme Open Air Museum.
*Source:* Veer (https://www.veer.com/) and VCG (https://www.vcg.com/).

catalysis but also aligns with the global pursuit of greener and more sustainable chemical processes.

### 4.3. Construction

Volcanic rocks have long been recognized as versatile materials in the construction industry, offering a range of applications from structural components to specialized insulation systems. Their unique properties, including high strength-to-weight ratios, resistance to environmental degradation, and thermal stability, have positioned them as indispensable resources for modern building technologies. Fig. 2 illustrates representative buildings incorporating volcanic rocks. This section explores the utilization of volcanic rocks in construction, emphasizing their mechanical, thermal, and acoustic performance, as well as their role in advancing sustainable and innovative architectural solutions.

#### 4.3.1. Structural components and materials

Volcanic rocks, such as basalt, pumice, and scoria, have been extensively utilized in structural applications due to their superior mechanical properties and durability [206–209]. Basalt, in particular, stands out for its exceptional strength-to-weight ratio and resistance to various environmental factors. One of the key uses of basalt is in the production of basalt fibers, which are derived through a high-temperature melting and extrusion process [37,210]. These fibers are widely employed as reinforcement materials in concrete and composite structures, significantly enhancing the tensile strength, flexural rigidity, and overall durability of the materials [211–215]. Additionally, basalt fibers exhibit excellent resistance to environmental stressors, including thermal cycles, chemical attacks, and UV degradation [216,217]. This non-reactivity and long-term stability make basalt fibers indispensable in constructing load-bearing elements such as bridges, foundations, and high-performance concrete structures [218–221]. Table 5 shows volcanic rocks in different aspects of structural components and aggregates.

In addition to their mechanical advantages, basalt-based components help reduce the overall weight of construction projects without compromising their structural integrity [222,223]. This enables the design of innovative, lightweight architectural frameworks that are not only strong but also energy-efficient. For instance, in the construction of bridges and high-rise buildings, basalt fiber-reinforced concrete has demonstrated superior crack resistance and durability, particularly in seismic-prone regions [224–226]. The incorporation of basalt fiber bars in concrete results in improved load distribution, reduced deformation under service loads, and an extended lifespan of structures, making them more resilient to extreme conditions [227,228]. Moreover, basalt-based concrete offers significant environmental benefits by reducing the need for conventional reinforcement materials, which often require energy-intensive manufacturing processes [229,230].

**Table 5**
Applications of volcanic rocks in structural components and aggregate.

| Application category | Specific use | Volcanic rock type | Advantages | Reference |
|---|---|---|---|---|
| Reinforced concrete | Basalt fiber-reinforced concrete, prestressed concrete beams, columns in high-rise buildings | Basalt | Enhanced tensile strength, excellent crack resistance, high durability; possesses high tensile modulus, chemical stability, and corrosion resistance | [39,244–246] |
| Bridge structures | Bridge support towers, pier foundations, load-bearing beams | Basalt, Andesite | Long-term durability, resistance to environmental erosion; features high compressive strength and abrasion resistance | [247–250] |
| Tunnel structures | Tunnel linings, permanent supports in basements | Basalt, Andesite | Resistance to thermal and mechanical stress; offers high thermal stability and durability | [251–253] |
| Lightweight construction | Lightweight wall panels, interior and exterior wallboards, lightweight roofing structures | Pumice | Reduced structural weight, improved seismic performance, ease of construction; characterized by low density and high energy absorption properties | [13,32,254–257] |
| Coastal protection | Wave breakers, hydraulic structures, riverbank stabilization structures | Basalt, Andesite | High durability, strong resistance to wave impact; has high density and abrasion resistance | [258–261] |
| Railway infrastructure | Subgrade stabilization aggregates, track foundation materials for rail systems | Basalt | Excellent compressive performance, strong load distribution; exhibits high compressive strength and durability | [261,262,262–267] |
| Historical restoration | Restoring historic volcanic stone structures such as ancient walls, bridges, and monuments | Obsidian, Tuff | Aesthetic and material compatibility; features natural texture and visual resemblance | [268–272] |

Furthermore, volcanic rock aggregates, such as basalt, pumice, and scoria, also play a crucial role in construction, particularly in ensuring the bulk and structural stability of concrete and asphalt mixtures [231,232]. These aggregates are highly valued for their angularity, which promotes better interlock and load transfer within composite matrices [233,234]. Volcanic rock aggregates are known for their high resistance to abrasion, fragmentation, and environmental degradation, making them ideal for use in heavy-duty applications such as roadways [235–237], highways [238,239], and airport runways [240,241]. In particular, basalt aggregates have been shown to significantly enhance the durability and performance of asphalt pavements, reducing maintenance requirements and extending the service life of infrastructure [242,243].

Zhou et al. conducted an experimental investigation into the mechanical properties of basalt fiber-reinforced concrete, focusing on its compressive, tensile, and flexural strengths, as well as its toughness and crack resistance performance [273]. Their findings revealed that incorporating basalt fibers significantly enhanced tensile and flexural strengths, with optimal improvements observed at fiber contents of 0.3% and 0.4%, leading to increases in compressive strength, tensile strength, and bending strength by 5.07%, 4.21%, and 42.34%, respectively.

Jing et al. investigated the enhancement of coal fly ash-based non-sintered lightweight aggregates using autoclave curing and $H_2O_2$-modified basalt fibers [274]. The optimized aggregates achieved a cylinder compressive strength of 15.52 MPa, a bulk density of 1089.83 kg/m$^3$, an apparent density of 1762.43 kg/m$^3$, and a 1-hour water absorption rate of 4.85%, surpassing Chinese standards for high-strength lightweight aggregates. The study revealed that autoclave curing promoted the formation of honeycomb-like $C-A-S-H$ gel, filling pores larger than 50 nm, while the roughened basalt fibers occupied pores in the 20–200 nm range.

Wongsa et al. investigated lightweight geopolymer concretes (LWGCs) using crushed clay brick (CA) and pumice aggregates (PA) as replacements for natural aggregates (NA) [275]. The study found that LWGCs containing CA achieved compressive strengths ranging from 8.2 MPa to 18.3 MPa with densities of 1685–1749 kg/m$^3$, while LWGCs with PA demonstrated compressive strengths of 2.7 MPa to 7.0 MPa and densities of 1011–1111 kg/m$^3$. These properties align with the requirements for structural lightweight concrete and lightweight moderate-strength concrete as per ACI Committee 213 standards. Additionally, CA and PA-based LWGCs exhibited superior thermal insulation and fire resistance compared to NA-based geopolymer concretes, maintaining higher residual strength at elevated temperatures of 400 °C, 600 °C, and 800 °C.

Wang et al. investigated the enhancement of recycled aggregate concrete using a composite addition of basalt fiber and nano-silica [276]. Their findings demonstrated that the optimal mechanical properties were achieved with 6% NS for a recycled aggregate replacement ratio of 50% and 8% NS for a 100% replacement ratio. At these levels, the density and interface transition zone performance of RAC were significantly improved, reducing porosity and enhancing compressive strength. Specifically, the inclusion of 1–2 kg/m$^3$ BF resulted in peak axial compressive and splitting tensile strengths at a 50% replacement ratio, while NS addition reduced the calcium–silicon ratio and strengthened the bond between fibers and the cement matrix.

Moreover, volcanic materials such as finely ground ash, basalt powder, and pumice are increasingly utilized as additives to improve the performance and sustainability of cementitious materials [277–279]. The pozzolanic properties of volcanic ash enable it to react with calcium hydroxide in cement, forming additional calcium silicate hydrate phases that enhance strength, density, and durability while reducing permeability to aggressive agents like chlorides and sulfates [280,281]. These chemical interactions not only extend the lifespan of structures in harsh environments but also mitigate alkali-silica reactions (ASR), improving the dimensional stability of concrete and preventing cracking [282–285].

Song et al. investigated the alkali activation of volcanic tuff combined with calcium-based materials and fly ash to optimize geopolymerization processes and elucidate reaction mechanisms [286]. The study revealed that the optimal mechanical performance was achieved with the addition of 10% CaO and 20% FA, resulting in maximum compressive strengths of 41.68 MPa at 28 days under a ratio of alkaline activator to basic mixture of 10:90. The incorporation of CaO shifted the Si–O–T (T = Al or Si) vibration band from 1101 cm$^{-1}$ to 1036 cm$^{-1}$, indicating calcium integration into the geopolymer matrix.

Ekinci et al. investigated the effects of nano silica, micro silica, and Styrene-Butadiene Latex on the mechanical, physical, and durability characteristics of volcanic tuff-based geopolymer concrete produced using NaOH and $Na_2SiO_3$+NaOH activation methods [287] . The study determined optimal additive ratios, with 2% NS and 5% SBL yielding the highest compressive strength, while MS exhibited the best performance at 5% for $Na_2SiO_3$+NaOH-activated samples and 3% for NaOH-activated samples. Compressive strength values reached a maximum of 32 MPa, while freeze-thaw resistance improved, with the best performance in $Na_2SiO_3$+NaOH-activated samples, showing only an 8.75% reduction in relative dynamic modulus after 300 cycles.

Cultrone investigated the incorporation of Mount Etna volcanic ash into clay mixtures for brick production, demonstrating that the addition of 10–20 wt% volcanic ash reduced kneading water requirements by up to 14% and improved durability, particularly against salt crystallization [288]. While the volcanic ash reduced compactness and compressive strength at lower firing temperatures, bricks fired at 1100 °C exhibited enhanced vitrification, achieving compressive strengths and durability exceeding recommended standards for ceramic materials, with the highest residue content yielding the most resistant bricks.

Seraj et al. explored the influence of particle size on the performance of pumice as a supplementary cementitious material [289], revealing that finer pumice particles significantly enhanced cement hydration rates, pozzolanic reactivity, and early-age compressive strength, with compressive strength gains up to 119% of control values at 28 days. However, finer particles increased plastic viscosity without affecting yield stress or alkali-silica reaction resistance.

#### 4.3.2. Thermal insulators

Volcanic rocks, such as pumice, perlite, obsidian, and basalt, are highly valued for their thermal insulation and fire-resistant properties [290–292]. The low thermal conductivity and high porosity of pumice and perlite enable their effective use in insulation panels, lightweight blocks, and plastering mortars [293–295]. These materials trap air within their microstructures, reducing heat transfer and maintaining indoor thermal comfort while minimizing energy consumption for heating and cooling [296,297]. Pumice-based insulation, in particular, has proven effective in mitigating thermal bridging in walls and roofs, contributing to energy-efficient building practices and green certifications [298].

The high-temperature stability and non-combustible nature of basalt and perlite make them ideal for fire-resistant applications [299,300]. Basalt fibers are extensively used in textiles and composite materials for fireproofing industrial panels, protective clothing, and building facades, maintaining structural integrity under extreme heat [301,302]. Similarly, expanded perlite is employed in fire-resistant plasters and lightweight blocks, acting as thermal barriers that protect underlying structures from heat damage [303–306]. The dual functionality of these materials–providing both thermal insulation and fire resistance–has been further enhanced through the development of hybrid materials combining basalt fibers with fire-retardant additives, meeting stringent safety and performance standards in modern construction [307–309].

Koçyiğit investigated the thermo-physical and mechanical properties of clay bricks enhanced with pumice and expanded vermiculite for energy-saving construction applications [310]. The study revealed that the addition of 40% pumice and 5% vermiculite reduced the thermal conductivity of the bricks by 58%, from 1.041 W $m^{-1}$ $K^{-1}$ to 0.439 W $m^{-1}$ $K^{-1}$, while increasing porosity by 52%. Despite a 24% reduction in compressive strength, the bricks maintained values (8.2–33.6 MPa) well above the structural standard of 7 MPa, demonstrating their dual suitability for insulation and load-bearing construction purposes.

Demirel optimized the composite brick structure composed of expanded polystyrene and pumice blocks to achieve superior thermal insulation and mechanical performance [311]. The study concluded that the optimal thickness for EPS and pumice layers was 40 mm and 20 mm, respectively, as this configuration minimized heat transfer while maintaining adequate compressive strength.

Liu et al. investigated the fabrication of 3D continuous basalt fiber architectures with fireproof and thermal insulation properties using additive manufacturing and a two-step precursor infiltration and pyrolysis process [312]. The study demonstrated that the final part, composed of continuous basalt fibers and a SiOC ceramic shell, achieved a shell temperature of 788.8 °C and an internal temperature of approximately 50 °C after 20 s of flame exposure, highlighting its superior fireproof and thermal insulation performance.

Prusakov et al. evaluated the fire resistance of super-thin basalt fiber-based sealing for expansion joints in reinforced concrete structures [292], focusing on performance under alternating deformation conditions. Their findings revealed that the fire-resistant cord, PROMIZOL-Shov-Sh150/240, achieved a fire resistance limit of EI 240, maintaining structural integrity and heat-insulating capacity for at least 245 min under a standard temperature regime, with an average unheated surface temperature of 140 °C.

Chen et al. investigated the fire resistance and economic feasibility of basalt fiber-reinforced thermal insulation mortar [313], demonstrating that the addition of 1.5% basalt fiber significantly enhanced the material's properties. The optimized mortar exhibited a 9.71% increase in compressive strength and an 11.1% reduction in mass loss after exposure to high temperatures. Moreover, the thermal conductivity and crack resistance were improved, while the production costs were reduced by up to 38.96% compared to market alternatives, showcasing its potential for sustainable and cost-effective construction applications.

Pei et al. investigated the mechanical and thermal insulation properties of geopolymer-based fireproof sandwich panels [314], finding that the addition of 10 wt% expanded vermiculite and 10 wt% expanded perlite to the geopolymer resulted in a compressive strength retention of 66.5% after exposure to 800 °C, along with a thermal conductivity of 0.1942 W/(mK) and a mass loss rate of only 4.83% under high-temperature conditions.

#### 4.3.3. Acoustic insulation

The inherent porosity and density of volcanic rocks, such as scoria and basalt, make them highly effective materials for acoustic insulation in both residential and commercial buildings [315–318]. These rocks are processed into soundproofing panels and barriers capable of absorbing and dampening sound waves, thereby reducing noise transmission between spaces [319,320]. With their high sound absorption coefficients, they are particularly suitable for walls, ceilings, and flooring systems in urban environments where noise pollution is a pressing concern [321,322]. Beyond interiors, volcanic rock-based acoustic materials find applications in industrial and public spaces, including manufacturing facilities, concert halls, and transportation hubs, where basalt fiber boards and scoria-filled partitions are used to create acoustically optimized environments. Their integration into soundproof walls not only enhances noise control but also contributes to improved quality of life, meeting modern architectural standards for comfort and functionality. Fig. 3 illustrates physical samples of basalt wool boards and pipes.

Song et al. investigated the preparation of softwood chemical pulp/basalt scales composite paper-based materials and their sound absorption and thermal insulation properties [323]. They found that when the basalt scale content was 30%, the maximum sound absorption coefficient reached 0.86 in the frequency ranges of 1200–1800 Hz and 2500–3400 Hz. Additionally, the thermal conductivity of the composite paper-based material decreased with increasing basalt scale content, and when the basalt scale content was 60%, the thermal conductivity reached 0.041 W/(m K), demonstrating excellent thermal insulation properties.

Jing et al. investigated the preparation of porous acoustic ceramics using magmatic soil, tuff, and glass powder as raw materials, with silicon carbide and straw powder serving as foaming and pore-forming agents, respectively [324]. The study found that the optimal conditions for sound absorption were achieved with a sintering temperature of 1150 °C, a holding time of 50 min, and a sample thickness of 30 mm. Under these conditions, the average sound absorption coefficient of the material was 0.34 across a frequency range of 200–4000 Hz, with the peak sound absorption coefficient reaching 0.68 at 1000 Hz.

Farouk et al. investigated the optimization of basalt-based fibers for thermal and acoustic insulation applications [325], and found that the mechanical properties of the produced wool boards exceeded EN standards by 28 times for compressive strength, 3 times for tensile strength, and 2.8 times for point load. Additionally, the thermal insulation characteristics of the wool boards were enhanced 1.30 times for thermal conductivity and 2.35 times for thermal resistance, while the acoustic properties showed a 1.10 times improvement in sound

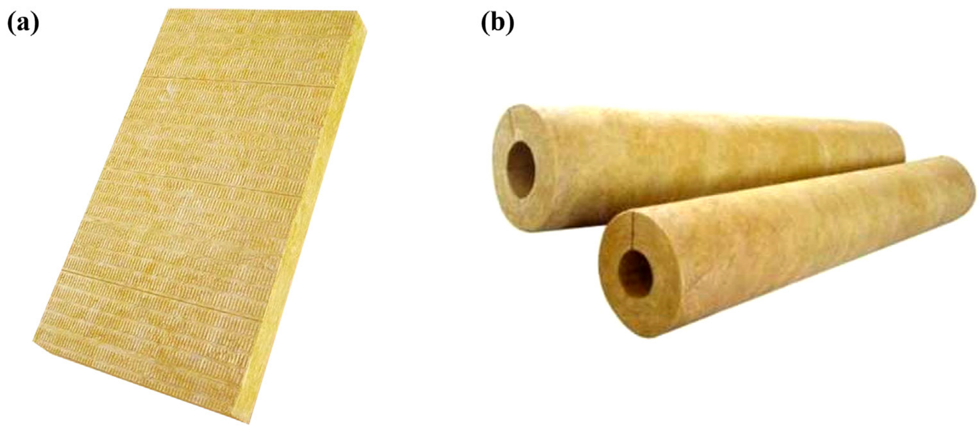

**Fig. 3.** Physical samples of basalt wool (a) boards and (b) pipes.
*Source:* Baidu B2B Procurement (https://b2b.baidu.com/).

absorption coefficient and a 1.40 times increase in Noise Reduction Coefficient.

Kapicová et al. developed sound-absorbing pervious concrete designed for interior acoustic panels [326], evaluating 29 different compositions to optimize acoustic and mechanical performance The study found that samples incorporating pumice aggregate (3–7 mm) achieved the highest noise reduction coefficient of 0.7, while a composition with mixed construction aggregate (4–8 mm), a water–cement ratio of 0.22, and added superplasticizer and silica fume provided a balance of promising sound absorption and sufficient mechanical strength. These findings offer valuable insights for developing lightweight, high-performance acoustic materials.

Ma et al. investigated the utilization of $\beta$-hemihydrate phosphogypsum as a raw material for preparing porous sound-absorbing materials (PSAM) [327]. The study revealed that the incorporation of 0.6 wt% pore-forming agent, 1 wt% basalt fiber, and 6 wt% expanded perlite significantly enhanced the sound absorption properties of PSAM by creating interconnected pores and introducing a cavity resonance structure. This optimized composition achieved a noise reduction coefficient compliant with the Chinese standard GB/T 16731–1997, demonstrating the potential for high-performance, environmentally friendly acoustic materials.

### 4.4. Culture

Volcanic rocks have been integral to various aspects of human civilization, serving multiple roles from practical applications to artistic expressions. Their unique properties, such as durability, sharpness, and aesthetic appeal, have been exploited in diverse fields. This section explores the historical and contemporary uses of volcanic rocks, demonstrating their versatility and enduring value.

#### 4.4.1. Tools

In historical contexts, the utilization of volcanic rocks as tools has been well-documented, illustrating the ingenuity with which ancient cultures exploited the inherent properties of these materials [328]. Obsidian, a volcanic glass, was particularly prized for its ability to fracture conchoidally, yielding edges of exceptional sharpness [329,330]. This quality was harnessed in the creation of tools and weapons, where the sharpness of the edge was a critical factor [331–333]. Artifacts such as knives, scrapers, and arrowheads (graphical schematic shown in Fig. 4) fashioned from obsidian have been unearthed in numerous archaeological sites, testifying to its widespread use across various continents.

Santi et al. conducted a comprehensive study on volcanic rock millstones [334], revealing their widespread use in ancient Mediterranean societies due to their superior grinding properties and availability, further highlighting the extensive trade networks and technological sophistication of these cultures.

Elizabeth Pintar et al. investigated obsidian use and mobility patterns during the Early and Middle Holocene in the Salt Puna region of northwest Argentina [335]. Their analysis of XRF data from obsidian artifacts across three archaeological sites revealed that during the Early Holocene, mobility was focused on a limited range of sources located within 40–95 km from the study area, with two primary sources identified in the eastern and northwestern regions. This mobility reflected early landscape learning. In contrast, the Middle Holocene phase, coinciding with climatic fluctuations and decreasing rainfall, showed an expanded range of obsidian sources, indicating increased knowledge of the landscape and a shift in territorial mobility patterns.

Walton conducted an experimental program with 145 obsidian tools, investigating their use-wear patterns in relation to 29 different materials available to pre-Hispanic residents of central Mexico [336]. The study demonstrated that initial use-wear patterns, such as those from slicing meat, fish, maize, and soft plants, can develop within just 5 min of tool use. Additionally, distinctive use-wear patterns were identified for maguey heart and leaf scraping, contributing new insights into ancient practices of pulque and fiber production.

Negash and Shackley conducted geochemical analyses of 31 obsidian artifacts from the Middle Stone Age site of Porc Epic, Ethiopia [337], and revealed that some of these artifacts were transported over distances of up to 250 km from their geological sources, providing evidence of extensive raw material procurement ranges and inter-group interactions as early as 77,000 years ago.

The remarkable compressive strength of basalt has made it a favored material in foundational applications. Its resilience and durability under pressure rendered it suitable for constructing buildings and infrastructural elements capable of withstanding substantial loads [338–341]. Additionally, basalt has been utilized in the production of tools, including flakes for cutting or scraping, as well as vessels for storage and other functional uses, underscoring its versatility and wide-ranging applications [342–345]. Basalt's utilization in these capacities has been observed in the remnants of early civilizations, where it formed the backbone of monumental architecture, enduring through the ages as silent sentinels of human engineering

Kirch et al. investigated the geochemical provenance of 328 basalt artifacts from the Kahikinui district on Maui Island [346], revealing that 27% of the tools originated from extra-local sources, including quarries on neighboring islands such as Hawai'i, O'ahu, Moloka'i, and Lāna'i.

Reti quantified Oldowan stone tool production at Olduvai Gorge, Tanzania, by establishing a null model for lithic artifact morphological variation through experimental replication of 219 cores, yielding 1758 flakes [347]. The study revealed that hominins produced quartzite


**Fig. 4.** Graphical schematic of obsidian tools.

flakes with greater efficiency compared to basalt flakes, indicating an economic awareness in mediating raw material procurement costs.

Volcanic tuff, softer and more carvable than other volcanic rocks, was often chosen for sculptural and architectural detailing [348–350]. Its workability when freshly quarried allowed artisans to achieve a level of detail unattainable with harder stones [351]. Tuff's versatility is evident in its use for creating intricate carvings and ornamental features in buildings, as well as standalone art pieces [352,353].

These examples underscore the multifaceted applications of volcanic rocks, reflecting not only the materials' physical characteristics but also the sophistication with which past cultures understood and manipulated these resources. The significance of volcanic rocks in the anthropological record thus testifies to their role in the technological evolution of human societies.

#### 4.4.2. Artistic and decorative

Volcanic rocks, with their rich textures and hues, have shaped artistic traditions from ancient Polynesian and Mesoamerican societies to contemporary art, transforming basalt, obsidian, and rhyolite into sculptures, relics, and adornments [354,355]. Basalt is chiseled into artifacts and architectural marvels [356,357], obsidian crafted into light-catching jewelry [358,359], and rhyolite fragments pieced together in mosaics [360], perpetuating a narrative of cultural heritage and craftsmanship.

In modern design, volcanic rocks connect spaces to the earth with timeless elegance, as exemplified by the basalt-inspired facade of Hallgrimskirkja Church in Reykjavik, the volcanic stone paving of the Gehry Partners-designed Facebook Headquarters in California, the integration of lava stone in the landscaping of the Jameos del Agua complex in Lanzarote, and the use of volcanic tuff in the award-winning Auckland Art Gallery in New Zealand. Additionally, fine grains and powders of volcanic origin are innovatively incorporated into ceramics, allowing artists to convey depth and texture [361–364]. This integration combines aesthetic appeal with structural strength, reflecting humanity's pursuit of beauty in nature's raw forms and ensuring the enduring legacy of these primordial materials.

### 4.5. Cosmetics and personal care

In the domain of personal care and cosmetology, the inherent characteristics of volcanic rocks have been harnessed to develop products that offer therapeutic benefits and enhance beauty regimens. The mineral-rich waters of volcanic hot springs, suffused with elements such as silica and sulfur, have long been sought after for their restorative properties [365–367]. These elements are known for their ability to support skin health [368], providing relief from various dermatological conditions and contributing to overall wellness. Spa retreats and wellness centers, often located near these volcanic sites, utilize the mineral-rich waters to offer treatments reputed to alleviate rheumatic pains [369] and promote cardiovascular health [370].

In cosmetic applications, volcanic clays and pumice are employed for their exfoliating and purifying effects on the skin. Volcanic clays gently remove dead skin cells, revealing a smoother and rejuvenated complexion, while their anti-inflammatory properties aid in reducing the appearance of fine lines and wrinkles [371]. Pumice, with its natural abrasiveness, is used as an exfoliant in skincare treatments, effectively removing dead skin cells to maintain healthy and radiant skin [372]. Finely ground pumice is utilized in toothpaste formulations to achieve controlled abrasiveness, facilitating safe teeth whitening while preserving enamel integrity [373]. Additionally, it serves as a critical raw material in the development of dental abrasion pastes, contributing to effective polishing applications in professional dental care [374,375]. Collectively, these applications exemplify the innovative use of natural resources in developing effective and environmentally conscious treatments. The exploration of these geological materials in modern cosmetology continues to expand, promising new and advanced applications that leverage their unique properties for health and beauty benefits.

## 5. Conclusions and future perspectives

The comprehensive examination of volcanic rocks has revealed their vast potential across multiple sectors, demonstrating their critical role in advancing sustainable development and technological innovation. Their unique physicochemical properties, such as high durability, thermal insulation, and rich mineral composition, make them highly suitable for diverse applications in industry, agriculture, construction, and environmental management. In industrial applications, volcanic rocks serve as effective catalysts and adsorbents, facilitating environmental remediation and pollution control. Their integration into construction materials has improved mechanical properties and sustainability, contributing to the creation of energy-efficient buildings and resilient infrastructure. Additionally, their aesthetic appeal and therapeutic properties have been harnessed in cultural and personal care products, reflecting their enduring value and versatility.

Looking forward, the future prospects for volcanic rock applications are promising, driven by ongoing research and technological advancements. The development of novel catalytic systems, enhanced construction materials, and environmentally friendly personal care products underscores their potential to contribute significantly to sustainable development. Interdisciplinary collaboration and policy support will be crucial in unlocking the full potential of volcanic rocks, promoting their responsible use, and integrating them into broader sustainability frameworks. As society advances, the strategic harnessing of volcanic rocks will be pivotal in addressing global challenges and building a more sustainable future.

## CRediT authorship contribution statement

**Hang Yang:** Writing – original draft. **Hongli Diao:** Writing – review & editing. **Shibin Xia:** Writing – review & editing.

## Consent for publication

The authors consent to publish this research.

## Ethics approval and consent to participate

The authors confirm that the manuscript has been read and approved by all authors. The authors declare that this manuscript has not been published and not under consideration for publication elsewhere. The authors have been personally and actively involved in substantive work leading to the manuscript and will hold themselves jointly and individually responsible for its content.

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Statement During the preparation of this work the authors used ChatGPT-4.0 in order to improve readability and language. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

All data generated or analyzed during this study are included in this published article.

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