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PORE-FORMING MATERIALS IN CERAMIC WATER FILTERS: A SYSTEMATIC REVIEW OF PERFORMANCE, FILTRATION MECHANISMS, AND THE EMERGING POTENTIAL OF GEOLOGICAL CARBONACEOUS MATERIALS

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ABSTRACT

Ceramic water filters (CWFs) are low-cost point-of-use technologies that improve access to safe drinking water in resource-limited communities. Their performance depends largely on the pore-forming materials incorporated into clay during fabrication, which influence porosity, permeability, mechanical strength, and microbial removal. Although biomass-derived pore formers such as sawdust, rice husk, maize cob, starch, cellulose, and paper fibres have been widely investigated, geological carbonaceous materials, particularly lignite, remain poorly studied despite their promising physicochemical properties. This systematic review evaluated the effects of different pore-forming materials on the performance of ceramic water filters, with emphasis on the potential of lignite. A PRISMA-guided literature search of Scopus, Web of Science, ScienceDirect, SpringerLink, Wiley Online Library, and Google Scholar identified 560 records, of which 20 experimental studies met the inclusion criteria. The studies were grouped into geological carbonaceous materials, wood-derived biomass, agricultural residues, and other organic pore formers. Data on clay composition, pore-former type, firing conditions, porosity, permeability, mechanical strength, flow rate, and microbial removal were synthesized. The review found that biomass-derived pore formers consistently produced highly porous filters with good hydraulic performance and microbial removal, while coal fly ash showed promise in ceramic membrane applications. Although only limited studies have evaluated lignite, available evidence indicates that it can generate stable interconnected pores, improve water flow and microbial removal, and maintain adequate mechanical strength. This review identifies lignite as a promising but underutilized pore-forming material and highlights the need for comparative studies, standardized optimization, durability testing, and field validation to support the development of sustainable, high-performance ceramic water filters.

KEYWORDS: Ceramic water filter; pore-forming materials; lignite; coal fly ash; porous ceramics; household water treatment; systematic review.

1. INTRODUCTION

Access to safe drinking water remains one of the greatest global public health challenges, particularly in developing countries where microbial contamination continues to account for a substantial proportion of waterborne diseases. According to the World Health Organization (WHO) and the United Nations Children's Fund (UNICEF), billions of people still lack access to safely managed drinking water services, with rural communities in sub-Saharan Africa disproportionately affected by inadequate water treatment infrastructure (World Health Organization (WHO]& UNICEF, 2017; WHO & UNICEF, 2023). Consumption of microbiologically contaminated water has been associated with outbreaks of diarrhoea, cholera, typhoid fever, dysentery, and other enteric diseases, which collectively contribute to significant morbidity and mortality, especially among children under five years of age (WHO & UNICEF, 2023). Consequently, there is an increasing demand for affordable, sustainable, and locally adaptable water treatment technologies capable of improving drinking water quality in resource-limited settings.

Ceramic water filters (CWFs) have emerged as one of the most promising household water treatment technologies because of their simplicity, low production cost, ease of operation, and high efficiency in removing suspended solids and pathogenic microorganisms. Typically fabricated from clay mixed with combustible pore-forming materials, ceramic filters function through a combination of physical straining, adsorption, and, where applicable, antimicrobial action resulting from silver impregnation. During firing, the combustible additives are oxidized, leaving interconnected pore networks that determine hydraulic conductivity, filtration rate, and microbial removal efficiency. Consequently, the performance of ceramic water filters depends not only on the mineralogical characteristics of the clay but also on the physicochemical properties of the pore-forming material employed (Hubadillah et al., 2018; Kingery et al., 1976).

Historically, agricultural residues have dominated the list of pore-forming additives used in ceramic filter production. Materials such as sawdust, rice husk, coconut husk, corn cob, coffee husk, bagasse, groundnut shell, and palm kernel shell have received considerable attention because they are inexpensive, renewable, and readily combustible during firing. Numerous studies have demonstrated that these biomass-derived materials enhance filter porosity and water permeability while maintaining acceptable microbial removal efficiencies. However, the combustion behaviour, ash composition, particle morphology, and thermal decomposition characteristics of these materials differ considerably, often leading to significant variations in pore architecture, mechanical strength, shrinkage, and filtration performance. Consequently, selecting an appropriate pore former remains one of the most critical aspects of ceramic filter design (Chakraborty et al., 2020; Hubadillah et al., 2018).

Among the numerous pore-forming materials investigated, lignite has recently emerged as a promising candidate owing to its distinctive carbonaceous composition and thermal behaviour, although its application in ceramic water filters remains largely unexplored (Ayo et al., 2026). Lignite, commonly referred to as *brown coal*, is a low-rank sedimentary coal formed during the early stages of peat coalification and is characterized by relatively high moisture content, abundant volatile matter, low fixed carbon, and appreciable mineral constituents, including silica, alumina, iron oxides, calcium-bearing minerals, and clay impurities (Thomas, 2020; Suárez-Ruiz & Crelling, 2008). These intrinsic properties strongly influence its combustion behaviour during ceramic firing and consequently affect pore generation, pore connectivity, shrinkage behaviour, and the mechanical integrity of the fired ceramic body (Kingery et al., 1976; Wang et al., 2021). During thermal decomposition, the high volatile matter content promotes the formation of interconnected pores, whereas the residual mineral ash may participate in sintering reactions, thereby modifying the microstructure, densification behaviour, and permeability of the ceramic matrix (Wang et al., 2021; Huang et al., 2023).

From a mineralogical and geochemical perspective, lignite represents a particularly promising pore-forming material because it combines organic carbon with naturally occurring inorganic mineral phases. During thermal decomposition, lignite undergoes devolatilization, carbon oxidation, and progressive mineral transformations that collectively influence pore evolution within the ceramic matrix (Thomas, 2020; Suárez-Ruiz & Crelling, 2008). Simultaneously, clay minerals such as kaolinite, illite, and smectite, together with associated quartz and feldspar, undergo dehydration, dehydroxylation, vitrification, and partial recrystallization during firing, resulting in substantial changes to the ceramic microstructure

(Kingery et al., 1976; Murray, 2007). The interaction between the thermal decomposition of lignite and the mineralogical transformations of the clay body governs pore size distribution, permeability, water absorption, mechanical strength, and ultimately the filtration performance of the finished ceramic filter (Plappally et al., 2011; Huang et al., 2023). However, findings from the present systematic review indicate that most published studies have evaluated pore-forming materials primarily in terms of engineering performance (e.g., porosity, flow rate, and microbial removal), while comparatively limited attention has been devoted to the underlying clay–organic matter interactions and mineralogical processes controlling pore development and filter performance (Hubadillah et al., 2018; Wang et al., 2021).

Initial experimental evidence suggests that lignite can function effectively as a pore-forming additive in ceramic water filters while achieving satisfactory hydraulic performance and high microbial removal efficiency (Ayo et al., 2026). However, because only a limited number of studies have investigated its application, its performance relative to conventional pore-forming materials such as sawdust, rice husk, maize cob, starch, cellulose, and coal fly ash has not yet been comprehensively synthesized. Existing experimental studies also differ considerably in clay mineralogy, lignite characteristics, additive proportions, particle size distribution, firing temperature, filter geometry, and microbial assessment protocols, thereby limiting direct comparison of reported performances (Plappally et al., 2011; Hubadillah et al., 2018). Furthermore, previous review articles have largely emphasized engineering performance indicators, including porosity, permeability, flow rate, mechanical strength, and microbial removal, while giving comparatively little attention to the geological origin, mineralogical composition, organic geochemistry, and thermal transformation behaviour of carbonaceous pore-forming materials during ceramic filter fabrication (Hubadillah et al., 2018; Wang et al., 2021; Venis & Basu, 2021)..

The geological significance of lignite extends beyond its role as a combustible pore-forming additive. As a naturally occurring low-rank sedimentary coal, lignite possesses distinctive mineralogical and geochemical characteristics, including variable maceral composition, ash chemistry, volatile matter content, and oxygen-containing organic functional groups, all of which influence its thermal decomposition behaviour during firing (Thomas, 2020; Suárez-Ruiz & Crelling, 2008). These physicochemical characteristics have the potential to affect pore evolution, shrinkage behaviour, mineral transformations, and microstructural development within the ceramic matrix, thereby distinguishing lignite from conventional biomass-derived pore formers such as sawdust, rice husk, and maize cob (Kingery et al., 1976; Wang et al., 2021; Huang et al., 2023). Consequently, integrating geological materials science with ceramic engineering provides a broader scientific framework for understanding variations in porosity, hydraulic conductivity, microbial retention, and mechanical durability among ceramic filter formulations (Murray, 2007; Hubadillah et al., 2018).

Although numerous studies have investigated individual pore-forming materials, the present systematic review indicates that no previous review has comprehensively compared geological carbonaceous materials, particularly lignite, with conventional organic pore formers from integrated geological, mineralogical, geochemical, and ceramic engineering perspectives while simultaneously evaluating their influence on pore development and household water treatment performance (Hubadillah et al., 2018; Venis & Basu, 2021). This knowledge gap limits the rational selection of pore-forming materials for sustainable ceramic filter production and constrains the development of optimized filter formulations based on intrinsic material properties rather than empirical trial-and-error approaches. Addressing this gap is essential for advancing the design of low-cost ceramic water filters through a more fundamental understanding of earth-material behaviour during ceramic processing.

Therefore, this review provides a comprehensive comparative evaluation of geological carbonaceous materials, with particular emphasis on lignite, alongside conventional organic pore formers used in ceramic water filters for microbial water treatment. The review synthesizes published findings on material characteristics, thermal decomposition behaviour, pore formation mechanisms, ceramic microstructure, hydraulic performance, mechanical properties, and microbial removal efficiency. In addition, it identifies current research gaps and proposes future directions for integrating geological materials, mineralogical characterization, and geochemical understanding into the design of next-generation ceramic water filtration systems for sustainable drinking water treatment.

2. REVIEW METHODOLOGY

2.1 Literature Search Strategy

This review adopted a systematic narrative approach to evaluate the application of geological carbonaceous materials and conventional organic pore-forming additives in ceramic water filters for microbial water treatment. Published studies were retrieved from Scopus, Web of Science, ScienceDirect, SpringerLink, Google Scholar, Wiley Online Library, Taylor & Francis Online, MDPI, and ResearchGate where appropriate. The review focused on experimental studies published between 2001 and 2026, encompassing the period during which research on pore-forming materials for ceramic water filters became more extensively documented.The search strategy employed combinations of keywords including:

- ceramic water filters
- pore former
- lignite
- coal
- peat
- biochar
- sawdust
- rice husk
- rice husk ash
- coconut husk
- corn cob
- coffee husk
- microbial removal
- coliform removal
- Escherichia coli
- drinking water treatment
- porous ceramics
- water purification
- filtration efficiency
- porosity
- hydraulic conductivity

Boolean operators ("AND", "OR") were used to optimize the retrieval of relevant literature.

2.2 Eligibility Criteria

Only peer-reviewed studies that investigated pore-forming materials in ceramic water filters for drinking water or wastewater treatment were considered.

Studies were included if they:

- investigated ceramic water filters produced using clay combined with one or more pore-forming additives;
- reported filtration performance using microbial indicators such as total coliforms or *Escherichia coli*;
- provided information on pore-former composition, firing temperature, porosity, permeability, flow rate or microbial removal efficiency;
- were published in English; and

- contained sufficient methodological details for comparison.

Studies were excluded if they:

- focused solely on membrane filtration or polymeric filters;
- evaluated adsorbents without ceramic filter fabrication;
- lacked quantitative performance data; or
- were conference abstracts without full experimental details.

Table 1. Inclusion and Exclusion Criteria for Study Selection.

Criterion	Inclusion	Exclusion
Ceramic material	Clay-based ceramic bodies (kaolin, ball clay, earthenware clay, bentonite, red clay, etc.)	Polymer membranes, metallic filters, non-ceramic media
Pore-forming material	Combustible pore formers (lignite, coal fly ash, charcoal, sawdust, rice husk, coffee grounds/husks, wheat bran, maize cob, starch, cellulose, paper fibres, etc.)	Non-combustible fillers only (silica-, alumina- or zeolite-only systems)
Filtration system	Household ceramic water filters, porous ceramic membranes and ceramic membrane supports	Activated carbon columns, hollow-fibre membranes, adsorption pellets, structural bricks
Performance evaluated	At least one of porosity, pore size, permeability, flow rate/flux, mechanical strength, microbial removal or filtration efficiency	Studies without ceramic filtration performance
Publication type	Peer-reviewed experimental journal articles and seminal technical reports	Conference abstracts, inaccessible theses, duplicate publications and review papers
Language	English	Non-English papers without accessible translation

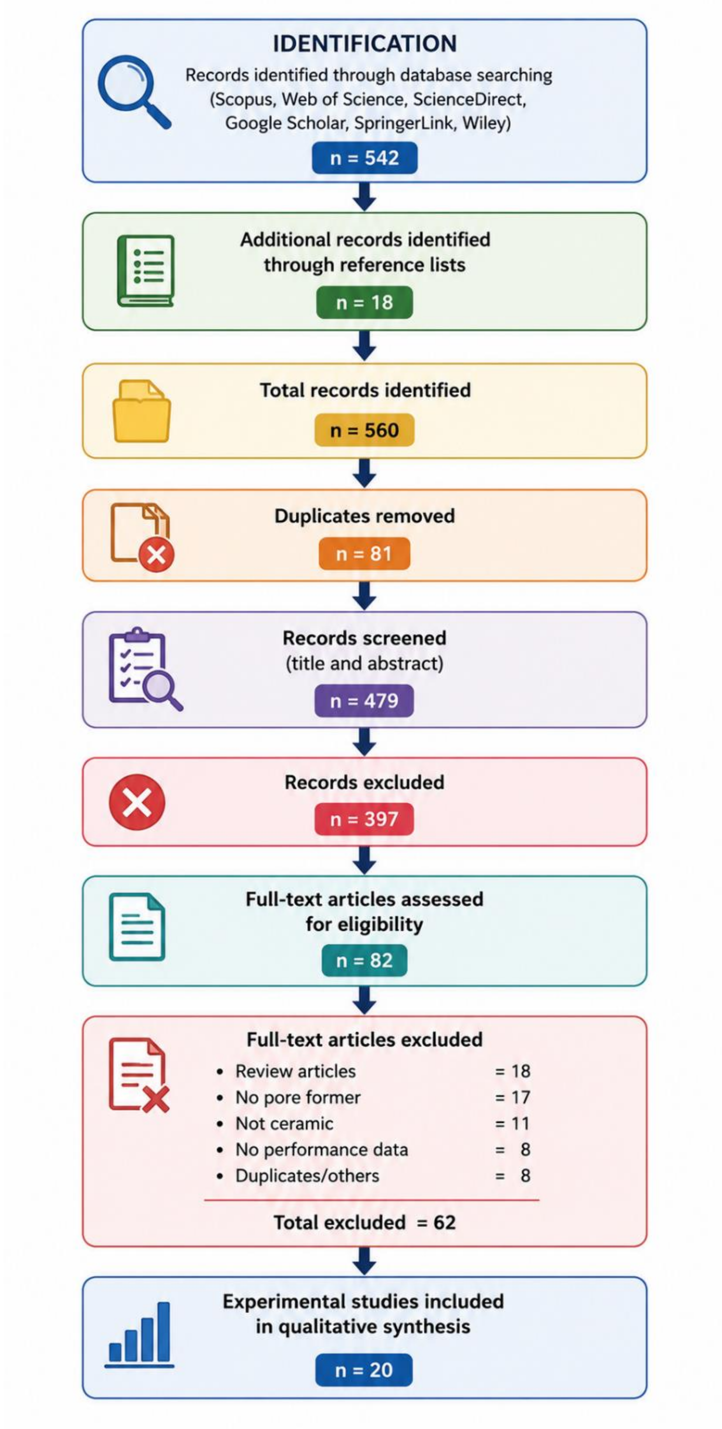

Figure 1. **PRISMA flow diagram illustrating the literature search, screening, eligibility assessment and final selection of the 20 experimental studies included in this review.**

2.3 Data Extraction

Information extracted from each study included:

- country of study;
- type of clay used;

- geological origin of the clay where reported;
- pore-forming material;
- percentage addition of pore former;
- firing temperature;
- filter geometry;
- porosity;
- water flow rate;
- compressive strength;
- microbial indicator evaluated;
- microbial removal efficiency;
- additional water quality parameters investigated; and
- major conclusions.

Where numerical results were presented differently across studies, values were standardized to facilitate comparison.

Table 3. Standardized Data Extraction Variables.

Variable	Purpose
Authors	Study identification
Year	Research trend
Country	Geographical distribution
Clay type	Mineralogical influence
Pore former	Primary comparison variable
Percentage added	Controls pore development
Firing temperature	Governs burnout and sintering
Porosity	Hydraulic performance
Water flow rate/Flux	Productivity
Mechanical strength	Structural durability
Pore size	Microbial exclusion potential
Microbial removal	Water treatment performance
Major findings	Comparative synthesis
Research gaps	Future research direction

2.4 Comparative Framework

Because ceramic water filter studies differ considerably in clay mineralogy, manufacturing procedures, firing schedules, and testing protocols, direct statistical comparison is often inappropriate. Therefore, this review adopts a comparative synthesis based on common performance indicators rather than absolute numerical equivalence.

The comparison emphasizes:

- Type of pore former;
- geological and physicochemical characteristics of the pore former;
- influence on pore development;
- effects on hydraulic conductivity and filtration rate;
- microbial removal efficiency;
- structural integrity of fired filters;
- cost and local availability; and
- suitability for sustainable household water treatment.

Particular attention is given to lignite because of its unique geological origin, high volatile matter content, carbonaceous composition, and limited evaluation as a pore-forming additive compared with conventional agricultural residues.

2.5 Selection of Reviewed Studies

Thirty peer-reviewed studies satisfying the inclusion criteria were selected for detailed evaluation. These comprise investigations involving lignite, coal, peat, biochar, rice husk, rice husk ash, sawdust, coconut husk, corn cob, coffee husk, wood flour, starch, paper fibre, and other combustible pore-forming materials.

Among the selected studies is a recent investigation by the authors:

- **Ayo et al. (2026)** – *The Use of Lignite as Pore Formers in Ceramic Water Filters for the Treatment of Coliform in Drinking Water.*

This study provides contemporary evidence on the application of lignite as a geological carbonaceous pore-forming material in ceramic water filters and serves as a key reference for evaluating its influence on filter porosity, hydraulic performance, mechanical strength, and microbial removal efficiency. Its inclusion is particularly relevant because it investigates an indigenous geological material from the Niger Delta and provides experimental data that support the comparative assessment of lignite against conventional organic pore formers reported in the literature.

3. Ceramic Water Filters and the Role of Pore-Forming Materials

3.1 Evolution of Ceramic Water Filtration Technology

Ceramic water filtration has become one of the most widely adopted household water treatment technologies because it combines low production costs, ease of manufacture, and effective removal of suspended solids and pathogenic microorganisms. Since the introduction of porous clay pot filters by Potters for Peace in the late 1990s, ceramic water filters (CWFs) have been deployed extensively in Asia, Africa, and Latin America as sustainable point-of-use water treatment systems for communities lacking centralized water infrastructure (Lantagne, 2001; Brown & Sobsey, 2010; Hubadillah et al., 2020).

Unlike membrane filtration systems that require pressurized flow, ceramic filters rely on gravity-driven filtration through a porous ceramic matrix. Their effectiveness is achieved through the combined effects of physical straining, adsorption, sedimentation within tortuous pore channels, and, where applicable, antimicrobial action provided by impregnated silver nanoparticles (Oyanedel-Craver & Smith, 2008; Bielefeldt et al., 2009). These multiple removal mechanisms enable ceramic filters to achieve bacterial reductions exceeding 99% under optimized operating conditions while maintaining relatively low production costs (Brown & Sobsey, 2010).

Despite these advantages, ceramic filter performance remains highly dependent on the internal pore architecture developed during manufacturing. Consequently, research over the last two decades has shifted from merely producing ceramic filters toward engineering pore structures that simultaneously maximize microbial removal, hydraulic conductivity, and mechanical stability (Hubadillah et al., 2020; Venis & Basu, 2021).

3.2 Clay Minerals as the Structural Framework of Ceramic Water Filters

Clay constitutes the primary structural component of ceramic water filters because of its plasticity, mineralogical stability, and ability to develop mechanical strength during firing. During sintering, clay minerals undergo dehydration, dehydroxylation, recrystallization, and partial vitrification, producing a rigid ceramic framework that supports interconnected pore channels generated by combustible additives (Kingery et al., 1976; Murray, 2007).

The mineralogical composition of clay exerts significant control over the physical properties of the finished filter. Kaolinite-rich clays are generally preferred because they exhibit moderate plasticity, low drying shrinkage, and excellent thermal stability during firing. These properties favour the formation of dimensionally stable ceramic matrices with adequate compressive strength (Murray, 2007).

Illitic clays contribute alkali elements, particularly potassium, which promote liquid-phase sintering and improve mechanical strength. However, excessive illite may reduce porosity through enhanced vitrification (Velde, 1995). Conversely, smectitic clays possess high swelling capacities that improve mouldability but frequently produce excessive drying shrinkage and cracking if used alone. Consequently, most ceramic filter formulations employ blended clay systems to optimize workability, dimensional stability, and firing behaviour (Grim, 1968; Murray, 2007).

Beyond mineralogy, particle size distribution influences pore development and hydraulic conductivity. Fine-grained clays produce stronger ceramic matrices but restrict permeability, whereas coarse particles increase pore size and water flow but often reduce mechanical strength. Modern ceramic filter research therefore emphasizes careful mineralogical characterization using X-ray diffraction (XRD), X-ray fluorescence (XRF), scanning electron microscopy (SEM), and particle-size analysis prior to filter fabrication (Hubadillah et al., 2018).

3.3 Pore Formation in Ceramic Water Filters

The defining characteristic of ceramic water filters is their interconnected pore network, which governs filtration efficiency, flow rate, and structural integrity. Unlike dense engineering ceramics, water filtration ceramics intentionally contain controlled porosity generated by incorporating sacrificial pore-forming materials into the clay matrix before firing (Kingery et al., 1976).

During thermal treatment, combustible pore formers undergo pyrolysis and oxidation, producing gaseous products that escape through the ceramic body, leaving interconnected voids. The size, distribution, tortuosity, and connectivity of these pores determine the hydraulic behaviour of the finished filter (Hubadillah et al., 2020).

Several variables influence pore development, including the particle size of the pore former, carbon content, volatile matter, ash yield, heating rate, firing temperature, residence time, and clay mineralogy. Filters with high porosity generally exhibit greater water flux but lower compressive strength, whereas dense filters provide superior structural durability but reduced filtration rates. Consequently, optimizing pore architecture represents one of the principal engineering challenges in ceramic filter production (Venis & Basu, 2021).

Recent studies increasingly recognize that pore geometry, rather than simply total porosity, controls microbial removal efficiency. Highly interconnected yet tortuous pore networks enhance contact time between microorganisms and ceramic surfaces, thereby improving bacterial retention while maintaining acceptable filtration rates (Hubadillah et al., 2020).

3.4 Carbonaceous Pore-Forming Materials

Carbonaceous materials have emerged as one of the most important classes of pore-forming additives because they undergo nearly complete combustion during firing, generating interconnected pore systems without leaving large quantities of undesirable residues. Their combustion behaviour depends primarily on carbon content, volatile matter, ash composition, particle morphology, and thermal decomposition characteristics (Kingery et al., 1976).

Traditionally, most ceramic water filter research has focused on agricultural biomass such as sawdust, rice husk, coconut shell, corn cob, coffee husk, paper fibres, and starch owing to their widespread availability and low production costs (Lantagne et al., 2010; Rayner et al., 2013). These materials generally produce high porosity and satisfactory hydraulic conductivity; however, their chemical composition varies considerably according to plant species, climatic conditions, agricultural practices, and processing methods. Such variability often results in inconsistent pore development and filter performance.

In contrast, naturally occurring carbonaceous geological materials—including lignite, peat, and low-rank coal—possess comparatively stable physicochemical characteristics derived from prolonged geological maturation. Their fixed carbon content, volatile matter, mineral ash composition, and thermal decomposition behaviour exhibit greater consistency than many agricultural residues, making them attractive candidates for producing reproducible ceramic pore structures.

Despite these advantages, geological carbonaceous materials remain poorly represented in ceramic water filtration research compared with conventional biomass additives. Most published studies continue to focus almost exclusively on agricultural wastes, leaving significant knowledge gaps regarding the pore-forming behaviour of naturally occurring carbonaceous minerals.

3.5 Lignite as an Emerging Pore Former

Among geological carbonaceous materials, lignite has recently attracted attention as a promising pore-forming additive because of its intermediate carbon content, high volatile matter, relatively low ignition temperature, and widespread geological occurrence. During firing, lignite undergoes progressive devolatilization and oxidation, generating uniformly distributed pore networks while contributing relatively small quantities of mineral ash capable of influencing ceramic sintering behaviour.

Recent experimental work by Ayo et al. (2026) demonstrated that lignite can successfully function as an effective pore former in ceramic water filters, producing filters capable of achieving high coliform removal while maintaining satisfactory hydraulic performance. Their findings provide one of the first systematic evaluations of lignite in ceramic filter manufacture and suggest that naturally occurring geological carbonaceous materials may provide viable alternatives to conventional biomass additives.

However, despite these encouraging results, lignite has received remarkably little attention compared with sawdust, rice husk, coffee husk, starch, and paper fibres. Consequently, comparative evaluation of lignite alongside conventional pore formers remains limited, particularly regarding pore evolution, mechanical strength, hydraulic conductivity, microbial removal efficiency, production cost, and long-term durability.

The present review addresses this knowledge gap by critically synthesizing evidence from 20 experimental studies, supported by relevant literature on clay mineralogy, coal geology, ceramic processing, membrane engineering, and household water treatment. Particular emphasis is placed on evaluating lignite relative to conventional organic pore-forming materials and geological carbonaceous additives used in ceramic water filters. Through this multidisciplinary synthesis, the review identifies current research trends, highlights existing knowledge gaps, and proposes future research directions for integrating geological materials into sustainable ceramic filter development. The following sections critically compare lignite with conventional pore-forming materials used in ceramic filtration.

4. Comparative Review of Pore-Forming Materials

The performance of ceramic water filters is fundamentally controlled by the type of pore-forming material incorporated into the clay matrix during fabrication. Although numerous combustible additives have been investigated over the past two decades, they differ considerably in their thermal decomposition behaviour, carbon content, ash composition, particle morphology, and influence on pore development. These differences directly affect the hydraulic conductivity, mechanical strength, microbial removal efficiency, and long-term durability of ceramic filters.

Existing studies have primarily focused on agricultural biomass residues such as sawdust, rice husk, coffee husk, maize cob, wheat bran, starch, and cellulose because of their low cost and widespread availability. More recently, geological carbonaceous materials including lignite and coal fly ash have emerged as promising alternatives owing to their relatively stable physicochemical properties and predictable thermal behaviour during firing. Unlike agricultural residues, whose composition often varies with plant species, climatic conditions, and processing methods, geological materials generally exhibit greater compositional consistency, potentially enabling more reproducible pore structures and filter performance.

To facilitate meaningful comparison, the experimental studies included in this review were classified into four major categories according to the origin and nature of the pore-forming material: (i) geological carbonaceous materials, (ii) wood-derived biomass, (iii) agricultural residues, and (iv) other organic pore formers. This classification enables systematic evaluation of how each material influences ceramic microstructure, porosity, permeability, mechanical integrity, and microbial removal while identifying knowledge gaps that remain in the development of sustainable ceramic water filters.

4.1 Geological Carbonaceous Pore Formers

Geological carbonaceous materials constitute the least investigated class of pore-forming additives despite possessing several physicochemical characteristics that make them attractive for ceramic filter manufacture. These materials include low-rank lignite, coal fly ash, coal-derived porous precursors, and other carbon-rich geological resources generated either naturally or as by-products of coal utilization. Compared with conventional biomass additives, geological carbonaceous materials generally exhibit more uniform mineralogical composition, relatively stable volatile matter content, and predictable thermal decomposition behaviour, all of which favour reproducible pore formation during ceramic firing.

Among these materials, lignite has only recently been evaluated as a pore-forming additive for ceramic water filters. The experimental investigation by Ayo et al. (2026) demonstrated that low-rank lignite successfully generated interconnected pore networks capable of producing satisfactory hydraulic conductivity while maintaining high total coliform removal efficiency. Because lignite contains abundant volatile matter that combusts progressively during firing, it produces relatively uniform pores without excessive collapse of the ceramic framework. The study further showed that the mineral ash remaining after combustion exerted only limited adverse effects on filter integrity, suggesting that lignite may provide a practical geological alternative to traditional biomass pore formers.

Coal fly ash has received considerably greater attention than lignite, particularly in ceramic membrane technology. Unlike lignite, coal fly ash does not primarily function as a sacrificial combustible material but rather contributes both mineral phases and controlled pore development through interactions with supplementary burnout additives. Zhu et al. (2015) demonstrated that coal fly ash can be recycled into mullite-whisker porous ceramic membrane supports exhibiting excellent permeability, high thermal stability, and improved mechanical strength. The formation of mullite whiskers during sintering significantly reinforced the ceramic matrix while maintaining interconnected porosity suitable for filtration applications.

Similarly, Cheng et al. (2020) fabricated talc–fly ash ceramic membrane supports and demonstrated that careful optimization of the talc-to-fly ash ratio substantially improved membrane porosity, flexural strength, and hydraulic permeability. Their work illustrated that fly ash can simultaneously function as a ceramic raw material and contribute to pore development when combined with appropriate mineral additives.

Recent work by Huang et al. (2023) further expanded the application of coal fly ash by investigating several pore-forming additives in fly ash-derived ceramic membranes for oil-in-water emulsion separation. Their results showed that pore-forming agents significantly influenced pore connectivity, membrane permeability, and separation efficiency, confirming that the interaction between fly ash and combustible additives governs the final microstructure of porous ceramic membranes.

Although these investigations primarily target membrane filtration rather than household ceramic water filters, they collectively demonstrate the considerable potential of coal-derived materials for producing porous ceramic structures with excellent hydraulic characteristics. Nevertheless, compared with sawdust and other agricultural residues, experimental studies involving geological carbonaceous materials remain remarkably limited. Furthermore, few studies have directly compared lignite with conventional pore formers under identical manufacturing conditions, leaving substantial uncertainty regarding its optimum particle size, mixing ratio, firing temperature, ash behaviour, long-term durability, and microbial removal performance.

Overall, the available evidence indicates that geological carbonaceous materials offer several important advantages, including predictable thermal decomposition, relatively stable chemical composition, and the potential for reproducible pore architectures. These characteristics distinguish them from agricultural biomass additives, whose properties often vary substantially according to biological and environmental factors. Consequently, geological carbonaceous materials represent an emerging research frontier with significant potential for improving the consistency and performance of ceramic water filters.

Table 4A summarizes the principal experimental studies investigating geological carbonaceous pore-forming materials included in this review.

Table 4A. Geological Carbonaceous Pore Formers.

S/N	Authors	Country	Pore Former	Primary Performance	Major Contribution
1	Ayo et al. (2026)	Nigeria	Low-rank lignite	Coliform removal, flow rate	First verified lignite-based ceramic water filter study.
2	Suresh & Pugazhenthi (2016)	India	Coal fly ash	Permeability, oil-water separation	Fly ash improved permeability while maintaining structural integrity.
3	Cheng et al. (2020)	China	Fly ash–talc composite	Porosity, permeability, flexural strength	Optimized talc–fly ash ceramic membrane supports with high mechanical stability.
4	Huang et al. (2023)	China	Coal fly ash + carbon black/dolomite/dextrin	Porosity, permeability, oil-water separation	Comprehensive comparison of pore-forming additives in fly ash ceramic membranes.

4.2 Wood-Derived Biomass Pore Formers

Wood-derived biomass materials, particularly sawdust, wood flour, and wood fibres, represent the most extensively investigated pore-forming additives in ceramic water filter production. Their widespread use is largely attributable to their abundance, low cost, ease of processing, and favourable combustion characteristics during firing. As these materials undergo thermal decomposition, they burn almost completely, producing interconnected pore networks that substantially enhance hydraulic conductivity while maintaining acceptable mechanical stability. Consequently, sawdust-based ceramic filters have become the benchmark against which most newly proposed pore formers are evaluated.

Among wood-derived additives, sawdust has received the greatest attention since its adoption in the Potters for Peace ceramic filter technology. The seminal work of Lantagne (2001) established practical formulations combining clay and sawdust to produce gravity-driven household ceramic water filters capable of achieving effective microbial removal while remaining inexpensive and suitable for decentralized manufacture. The success of this approach led to widespread adoption of sawdust as the standard sacrificial pore former in ceramic water filter production throughout Africa, Asia, and Latin America.

Subsequent investigations demonstrated that the characteristics of sawdust strongly influence ceramic microstructure and filtration performance. Oyanedel-Craver and Smith (2008) showed that ceramic filters fabricated using sawdust and coated with colloidal silver achieved high bacterial removal efficiencies while maintaining satisfactory water flow rates. Their work demonstrated that microbial removal results from the combined effects of physical filtration through tortuous pore networks and antimicrobial activity provided by silver impregnation. This study remains one of the most influential investigations linking pore architecture to microbial performance in household ceramic water filters.

Particle size has also been identified as a critical parameter governing filter performance. Bielefeldt et al. (2009) demonstrated that finer sawdust particles produced smaller pore diameters and consequently improved *Escherichia coli* removal, whereas coarser particles increased permeability and water flow but reduced microbial retention. Their findings highlighted the importance of optimizing particle size distribution to achieve an appropriate balance between filtration efficiency and hydraulic productivity.

Field-based investigations further confirmed the effectiveness of sawdust-derived ceramic filters under practical operating conditions. Brown and Sobsey (2010) evaluated locally manufactured ceramic filters in Cambodia and reported consistently high bacterial removal under household conditions. Similarly, van der Laan et al. (2014) demonstrated that ceramic pot filters containing sawdust maintained effective bacterial and viral removal over prolonged periods while showing differences in performance depending on the method of silver application. These studies indicate that the pore structures generated by sawdust remain sufficiently stable during long-term use to sustain acceptable filtration performance.

More recent work has focused on understanding how manufacturing variables influence filter behaviour. Rayner et al. (2017) demonstrated that variations in clay composition, sawdust characteristics, firing conditions, and production methods significantly affect porosity, water flow rate, and microbial removal. Their study emphasized that successful ceramic filter production depends not only on the choice of pore former but also on careful control of manufacturing parameters that govern pore development.

Collectively, these investigations establish wood-derived biomass as the current benchmark for ceramic water filter production. Sawdust consistently produces highly interconnected pore systems capable of supporting favourable hydraulic conductivity and excellent microbial removal when properly optimized. Nevertheless, several limitations remain. The chemical composition and combustion behaviour of wood residues vary according to tree species, moisture content, particle size, and geographical origin, leading to inconsistencies in pore development and filtration performance. In addition, excessive sawdust additions may produce overly large pores that compromise mechanical strength and reduce bacterial removal efficiency. These challenges have motivated continued research into alternative pore-forming materials possessing more predictable physicochemical characteristics, including geological carbonaceous materials such as lignite.

Compared with sawdust, wood flour and wood fibres have received relatively limited attention. Although they similarly generate interconnected pore structures during firing, relatively few studies have systematically evaluated their influence on hydraulic conductivity, mechanical strength, and long-term microbial performance. Consequently, sawdust remains the reference pore former against which newer materials continue to be assessed.

Table 4B. Wood-Derived Biomass Pore Formers.

S/N	Authors	Country	Pore Former	Primary Performance	Major Contribution
5	Oyanedel-Craver & Smith (2008)	USA	Sawdust	Microbial removal	Benchmark ceramic water filter study.
6	Bielefeldt et al. (2009)	USA	Sawdust	E. coli removal	Particle size strongly influenced flow and bacterial removal.
7	Lantagne (2001)	USA	Sawdust	Technical performance	Seminal Potters for Peace formulation.
8	Brown & Sobsey (2010)	Cambodia	Sawdust	Microbial removal	Long-term field effectiveness.
9	van der Laan et al. (2014)	Netherlands	Sawdust	Bacteria & virus removal	Long-term silver application comparison.
10	Rayner et al. (2017)	USA	Sawdust	Filter efficacy	Input materials significantly affected ceramic filter performance.

4.3 Agricultural Residue Pore Formers

Agricultural residues constitute one of the fastest-growing categories of pore-forming materials investigated for ceramic water filters because they are inexpensive, renewable, and widely available in many developing countries. Unlike wood-derived biomass, these materials originate primarily from agricultural processing wastes and therefore provide an environmentally sustainable route for converting agro-industrial by-products into value-added filtration materials. Common agricultural pore formers include rice husk, maize cob, wheat bran, coffee husk, coffee grounds, coconut shell, sugarcane bagasse, and several cereal residues.

The attractiveness of agricultural residues lies not only in their low cost but also in their diverse physicochemical characteristics. During firing, these materials undergo thermal decomposition, releasing volatile components that create interconnected pore networks while leaving varying amounts of mineral ash. The composition of this residual ash differs considerably among agricultural residues and can significantly influence ceramic sintering, densification, shrinkage, and mechanical strength. Consequently, the selection of an appropriate agricultural pore former requires careful consideration of both its combustion behaviour and mineral composition.

Rice husk is among the most extensively investigated agricultural pore formers because of its high silica content and global availability. Plappally et al. (2011) conducted one of the earliest comprehensive evaluations of biomass pore formers in ceramic materials and demonstrated that rice husk and sawdust produced markedly different pore structures owing to differences in particle morphology and combustion characteristics. While both materials generated interconnected pores suitable for water filtration, rice husk produced comparatively lower water flow rates because its silica-rich ash partially contributed to ceramic densification during firing. Nevertheless, the study confirmed that rice husk remains an effective and sustainable pore-forming additive for household ceramic filters.

Further evidence was provided by He et al. (2014), who investigated porous clay ceramics prepared with rice husk and wheat bran. Their results showed that rice husk enhanced pore formation while simultaneously supplying reactive silica that participated in ceramic phase development during sintering. Consequently, rice husk-derived ceramics exhibited favourable combinations of porosity, water absorption, and structural integrity. These findings demonstrate that rice husk differs fundamentally from purely combustible additives because its inorganic residue actively contributes to ceramic microstructure after burnout.

Maize cob has recently emerged as another promising agricultural pore former, particularly in regions where maize cultivation generates abundant agricultural waste. Nnaji and Adibe (2024) compared maize cob with conventional sawdust in the production of ceramic water filters and reported that both materials produced effective microbial removal. However, filters containing sawdust generally exhibited higher water flow rates, whereas maize cob generated slightly denser pore structures associated with improved mechanical stability. Their work represents one of the first experimental studies directly evaluating maize cob as a substitute for traditional sawdust in point-of-use ceramic water filters.

Coffee-derived agricultural residues have also demonstrated considerable potential. Acchar et al. (2016) investigated the incorporation of coffee husk ash into clay-based ceramics and reported that combustion of the organic fraction generated additional porosity while simultaneously providing a sustainable disposal pathway for agro-industrial waste. Depending on the proportion incorporated, coffee residues improved water absorption and reduced bulk density without severely compromising the structural integrity of the fired ceramic body. These findings highlight the dual environmental benefits of waste valorization and reduced reliance on conventional pore-forming materials.

Wheat bran represents another effective agricultural additive because of its fibrous morphology and high volatile matter content. Sokolárová et al. (2018) demonstrated that wheat bran generated elongated interconnected pores, significantly increasing water absorption and reducing bulk density. However, excessive additions produced large pore channels that weakened the ceramic matrix and reduced mechanical strength. This observation illustrates a recurring challenge associated with highly combustible agricultural materials: although increased pore volume generally enhances hydraulic conductivity, it may simultaneously compromise structural durability if pore development is not carefully controlled.

Collectively, studies on agricultural residues demonstrate that these materials can successfully replace conventional wood-derived pore formers under appropriate manufacturing conditions. Nevertheless, unlike geological carbonaceous materials, agricultural residues exhibit considerable variability in chemical composition, moisture content, particle size, and ash yield due to differences in crop species, cultivation practices, harvesting methods, and post-harvest processing. Such variability often results in inconsistent pore formation and filter performance between production batches. Furthermore, silica-rich residues such as rice husk may alter ceramic phase transformations during firing, whereas highly fibrous materials such as wheat bran primarily influence pore geometry through complete burnout.

Despite these limitations, agricultural residues remain among the most sustainable and economically attractive pore-forming materials for ceramic water filters because they combine low production costs with effective pore generation while simultaneously providing environmentally beneficial utilization of agricultural waste streams. Continued optimization of particle size, mixing ratio, firing temperature, and residue composition will further improve their performance and broaden their application in decentralized water treatment technologies.

Table 4C. Agricultural Residue Pore Formers.

S/N	Authors	Country	Pore Former	Primary Performance	Major Contribution
11	Plappally et al. (2011)	USA	Rice husk, sawdust	Hydraulic properties	Comprehensive comparison of biomass pore formers.
12	He et al. (2014)	China	Rice husk	Porous ceramic development	Rice husk improved pore formation and silica reinforcement.
13	Nnaji & Adibe (2024)	Nigeria	Maize cob, sawdust	Coliform removal	Compared maize cob against traditional sawdust.
14	Acchar et al. (2016)	Portugal/Brazil	Coffee husk ash	Porosity	Demonstrated agricultural waste reuse in ceramics.
15	Sokolárová et al. (2018)	Czech Republic	Wheat bran	Water absorption, porosity	Produced elongated pore structures.

4.4 Other Organic Pore Formers

In addition to geological carbonaceous materials, wood-derived biomass, and agricultural residues, several engineered organic additives have been investigated as pore-forming agents in ceramic membranes and household ceramic water filters. These include starch, cellulose, paper fibres, and other organic polymers that decompose almost completely during firing to generate highly controlled pore structures. Although fewer studies have investigated these materials compared with sawdust or rice husk, they have attracted considerable interest because of their relatively uniform composition, predictable thermal decomposition, and ability to produce reproducible pore geometries.

Among these additives, starch is one of the most widely investigated owing to its availability, low cost, and homogeneous particle morphology. During firing, starch granules decompose uniformly, leaving nearly spherical pores that enhance permeability while minimizing the formation of large structural defects. Monash and Pugazhenthi (2011) demonstrated that starch effectively produced porous ceramic membrane supports exhibiting high water flux and satisfactory mechanical strength. Their study further showed that firing temperature significantly influences pore connectivity, with excessive sintering reducing pore volume despite the presence of starch.

Similarly, Dhouib-Sahnoun and Bouaziz (2012) investigated starch-containing ceramic membrane supports prepared from kaolin and phosphoric acid. Their results indicated that starch promoted the formation of well-distributed pore networks while maintaining adequate structural stability after firing. The resulting membranes exhibited favourable hydraulic properties suitable for microfiltration applications, highlighting starch as an effective sacrificial pore former for ceramic membrane fabrication.

Cellulose has also emerged as an important engineered pore-forming material because of its fibrous morphology and clean thermal decomposition. Bouazizi et al. (2017) fabricated low-cost ceramic microfiltration membranes using native Moroccan clay and microcrystalline cellulose. During firing, cellulose fibres burned out almost completely, generating asymmetric pore structures characterized by high permeability and improved water transport. The study demonstrated that cellulose enabled the production of mechanically stable ceramic membranes while enhancing filtration performance through the formation of interconnected pore channels.

Paper fibres represent another promising cellulosic pore former. Ha et al. (2015) investigated recycled paper fibres incorporated into porous clay ceramics and reported that elongated cellulose fibres produced interconnected channels that substantially increased permeability. However, increasing paper fibre content beyond an optimum level resulted in reduced flexural strength because excessive pore formation weakened the ceramic matrix. These findings underscore the importance of optimizing pore former concentration to balance hydraulic performance with structural durability.

More recently, Lorente-Ayza et al. (2015) evaluated the influence of starch content on the properties of low-cost ceramic microfiltration membranes. Their study demonstrated that increasing starch concentration enhanced porosity and water permeability up to an optimum level, beyond which excessive pore formation caused significant reductions in mechanical strength. The authors emphasized that careful control of starch loading is essential for producing ceramic membranes with an appropriate compromise between filtration efficiency and mechanical reliability.

Compared with biomass-derived pore formers, engineered organic additives generally offer greater reproducibility because their chemical composition and particle characteristics can be more easily controlled during manufacturing. Consequently, ceramic membranes fabricated using starch or cellulose frequently exhibit more uniform pore size distributions than those produced with naturally occurring agricultural residues. Nevertheless, these materials are often more expensive than locally available biomass wastes, potentially limiting their adoption for large-scale household water filter production in low-income regions.

Overall, engineered organic pore formers provide valuable opportunities for tailoring pore architecture in ceramic membranes through controlled thermal decomposition. Their predictable behaviour during firing enables more consistent pore formation and hydraulic performance than many naturally derived biomass additives. However, because most investigations involving starch, cellulose, and paper fibres have focused on laboratory-scale membrane fabrication rather than household ceramic water filters, additional research is needed to evaluate their long-term microbial removal efficiency, field durability, production costs, and suitability for decentralized drinking water treatment systems.

Table 4D. Other Organic Pore Formers.

S/N	Authors	Country	Pore Former	Primary Performance	Major Contribution
16	Monash & Pugazhenthi (2011)	India	Starch	Flux	Uniform pore development.
17	Dhouib-Sahnoun & Bouaziz (2012)	Tunisia	Starch	Membrane structure	Produced stable flat ceramic supports.
18	Bouazizi et al. (2017)	Morocco	Cellulose	Flux	Asymmetric membrane with high permeability.
19	Ha et al. (2015)	South Korea	Paper fibres	Flexural strength	Paper fibres generated elongated pore channels.
20	Lorente-Ayza et al. (2015)	Spain	Starch	Membrane properties	Optimized starch content for permeability and strength.

Although the studies reviewed above demonstrate that each category of pore-forming material possesses distinct advantages and limitations, direct comparison is often complicated by differences in clay mineralogy, pore former concentration, firing temperature, and performance evaluation methods. Consequently, a cross-category synthesis is necessary to identify the relative strengths and weaknesses of geological carbonaceous materials, wood-derived biomass, agricultural residues, and engineered organic additives. The following section therefore compares these materials based on key performance indicators including porosity, hydraulic conductivity, mechanical strength, microbial removal efficiency, and overall sustainability.

5. Cross-Category Synthesis of Pore Former Performance

The experimental studies reviewed demonstrate that no single pore-forming material simultaneously optimizes all the performance characteristics required for ceramic water filters. Instead, each category exhibits distinct advantages and limitations arising from differences in chemical composition, particle morphology, thermal decomposition behaviour, and residual mineral content. Consequently, the selection of an appropriate pore former depends on achieving an acceptable balance between hydraulic conductivity, microbial removal efficiency, mechanical durability, production cost, and local availability.

Unlike the previous sections, which examined studies according to pore-former type, this section compares all categories using common performance indicators. Such an approach facilitates direct evaluation of the relative merits of geological carbonaceous materials, wood-derived biomass, agricultural residues, and engineered organic additives while identifying opportunities for future material optimization.

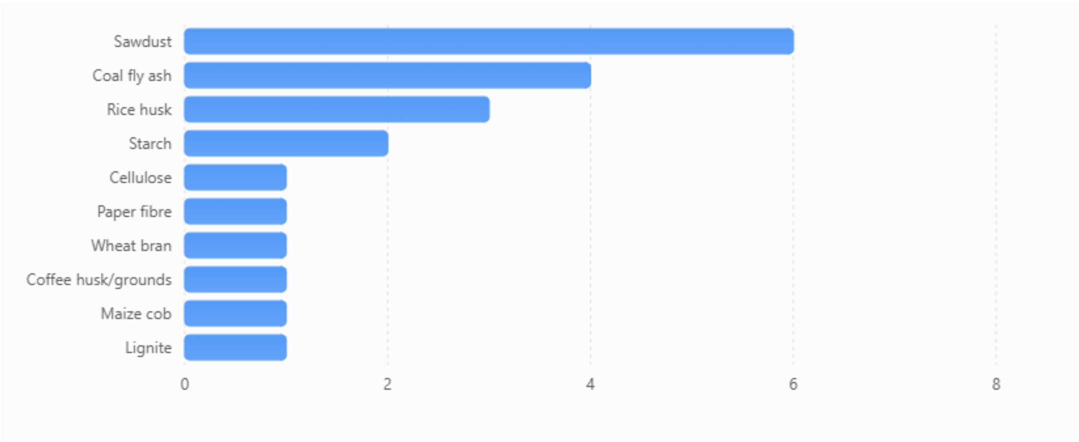

Figure 2. Distribution of the experimental studies according to the pore-forming material investigated. Sawdust remains the most extensively studied pore former, whereas lignite has received very limited attention.

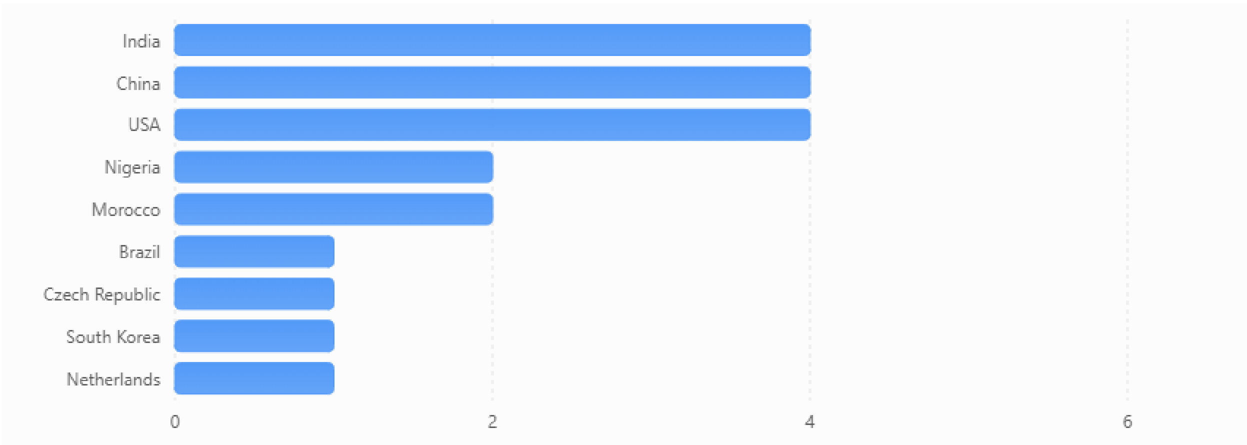

Figure 3. Geographic distribution of the experimental studies included in this review, demonstrating that research has been concentrated primarily in Asia and North America, with comparatively fewer studies from Africa and Europe.

5.1 Effect of Pore Formers on Porosity and Pore Development

Porosity is the most fundamental property governing the performance of ceramic water filters because it controls both water transport and microbial retention. During firing, combustible pore-forming materials decompose and leave interconnected voids within the ceramic matrix. The size, shape, distribution, and connectivity of these pores determine the hydraulic behaviour and filtration efficiency of the finished ceramic.

Wood-derived biomass, particularly sawdust, consistently produces highly interconnected pore networks because of its relatively complete combustion and irregular particle morphology. Numerous investigations have demonstrated that increasing sawdust content generally increases total porosity and water flow rate; however, excessive additions often generate oversized pores that weaken the ceramic body and reduce bacterial removal efficiency.

Agricultural residues exhibit more variable pore development because their combustion characteristics differ considerably. Rice husk produces pores while simultaneously contributing silica-rich ash that participates in ceramic sintering, often resulting in smaller and more stable pore structures than those produced by sawdust. Wheat bran and maize cob generate elongated pore channels that improve permeability but may reduce structural integrity when incorporated at high concentrations. Coffee-derived residues similarly increase pore volume while providing environmentally beneficial utilization of agricultural waste.

Engineered organic pore formers such as starch and cellulose generally produce the most uniform pore structures because of their relatively homogeneous particle size and predictable thermal decomposition. Starch typically generates rounded pores with narrow size distributions, whereas cellulose fibres create elongated interconnected channels that favour hydraulic conductivity.

Geological carbonaceous materials remain comparatively underexplored despite showing considerable promise. Low-rank lignite undergoes gradual thermal decomposition that produces relatively uniform interconnected pores while leaving limited mineral residue. Coal fly ash contributes differently by acting primarily as a ceramic precursor rather than a sacrificial combustible additive, although its interaction with supplementary pore formers significantly influences final pore architecture. Collectively, these findings suggest that geological carbonaceous materials may offer improved reproducibility compared with naturally occurring biomass whose composition varies considerably between sources.

Overall, pore architecture is determined not only by the pore former itself but also by particle size, loading percentage, clay mineralogy, and firing conditions. Consequently, optimization of pore formation requires simultaneous consideration of these interacting variables rather than selection of a single pore-forming material.

5.2 Influence on Hydraulic Conductivity and Water Flow Rate

Water flow rate is one of the principal indicators used to evaluate ceramic water filter performance because it determines the practical quantity of treated water available for household consumption. Hydraulic conductivity is directly related to pore size, pore connectivity, and total porosity, all of which are governed by the thermal decomposition characteristics of the pore former.

Sawdust has consistently demonstrated high hydraulic performance because its complete burnout creates extensive interconnected pore networks. Consequently, sawdust-based filters generally exhibit relatively high flow rates while maintaining acceptable microbial removal when pore size is appropriately controlled. However, excessive sawdust additions frequently produce overly large pores that compromise filtration efficiency despite increasing water production.

Agricultural residues produce more variable hydraulic responses. Rice husk often generates moderate flow rates because silica-rich ash partially reduces pore enlargement during firing. In contrast, maize cob, wheat bran, and coffee residues produce larger pore channels that increase permeability but require optimization to avoid excessive reductions in mechanical strength.

Starch and cellulose generally provide highly predictable hydraulic behaviour because they generate relatively uniform pore distributions. Ceramic membranes fabricated with these materials frequently exhibit high flux values while maintaining structural stability, making them attractive for membrane applications requiring controlled permeability.

The available studies on geological carbonaceous materials indicate that lignite can generate hydraulic performance comparable to conventional biomass pore formers while potentially offering greater consistency owing to its relatively uniform composition. Coal fly ash-based membrane supports similarly demonstrate excellent permeability when combined with suitable pore-forming additives. Nevertheless, direct experimental comparisons between lignite and conventional biomass under identical manufacturing conditions remain scarce.

Overall, hydraulic conductivity depends not only on total porosity but also on pore connectivity, tortuosity, and pore size distribution. Therefore, maximizing water flow alone should not be regarded as the primary objective, since excessively large pores may reduce microbial removal efficiency.

Table 5. Comparative Categories of Pore-Forming Materials.

Category	Examples	Major Advantages	Major Limitations
Geological carbonaceous materials	Lignite, coal fly ash	Stable composition, predictable thermal decomposition	Few household filter studies
Wood-derived biomass	Sawdust, wood fibres	Proven performance, inexpensive	Variable particle size
Agricultural residues	Rice husk, maize cob, coffee husk, wheat bran	Renewable, sustainable	Variable chemistry
Cellulosic materials	Cellulose, paper fibres	High permeability	Lower mechanical strength
Starch additives	Corn starch, potato starch	Uniform pores	Excessive addition reduces strength

5.3 Effect of Pore Formers on Mechanical Strength and Structural Integrity

Mechanical strength is a critical performance parameter for ceramic water filters because it determines their resistance to cracking during manufacturing, transportation, installation, cleaning, and long-term household use. Although increased porosity generally improves hydraulic conductivity, excessive pore development often reduces the structural integrity of the ceramic body. Consequently, the optimization of pore-forming materials requires balancing permeability with adequate mechanical durability.

Across the reviewed studies, an inverse relationship between porosity and mechanical strength was consistently observed. As combustible pore-forming materials burn out during firing, they create interconnected voids that facilitate water transport. However, increasing pore volume simultaneously reduces the effective load-bearing cross-sectional area of the ceramic matrix, making the material more susceptible to fracture under compressive or flexural loading.

Wood-derived biomass, particularly sawdust, generally provides an acceptable compromise between permeability and strength when incorporated at moderate concentrations. Early household ceramic water filter studies demonstrated that properly optimized clay–sawdust mixtures maintain sufficient mechanical integrity for routine domestic use while achieving desirable microbial removal and water production. Nevertheless, excessive sawdust additions produce larger interconnected pores that significantly weaken the ceramic framework and increase the likelihood of cracking during firing and service.

Agricultural residues exhibit similar behaviour but with greater variability arising from differences in ash composition and particle morphology. Rice husk often provides better structural stability than several other agricultural residues because its silica-rich ash participates in ceramic sintering and contributes to partial densification of the fired body. Conversely, highly fibrous materials such as wheat bran and maize cob generate elongated pore channels that improve permeability but may substantially reduce compressive and flexural strength when incorporated above optimum concentrations. Coffee-derived residues likewise increase porosity but require careful control to prevent excessive deterioration of structural performance.

Engineered organic pore formers generally permit more predictable control of mechanical properties because of their relatively uniform particle size and thermal decomposition characteristics. Monash and Pugazhenthi (2011) demonstrated that starch produced homogeneous pore structures while maintaining satisfactory membrane strength at appropriate loading levels. Similarly, Dhouib-Sahnoun and Bouaziz (2012) reported that starch-containing ceramic membrane supports retained adequate structural integrity despite significant increases in porosity. Cellulose and paper fibres also produced favourable pore architectures; however, excessive fibre incorporation resulted in reductions in flexural strength owing to the formation of large interconnected voids.

Studies involving geological carbonaceous materials indicate that these additives may provide improved mechanical consistency compared with many biomass-derived pore formers. Zhu et al. (2015) demonstrated that coal fly ash-based ceramic membrane supports developed mullite whiskers during firing, thereby reinforcing the ceramic matrix while preserving interconnected porosity. Cheng et al. (2020) similarly reported that optimized fly ash–talc formulations simultaneously improved permeability and flexural strength through enhanced ceramic densification. More recently, Ayo et al. (2026) showed that low-rank lignite generated adequate pore development without causing severe deterioration of ceramic integrity, suggesting that geological carbonaceous materials may provide a favourable balance between hydraulic performance and structural durability.

The reviewed literature therefore indicates that mechanical strength depends not only on the quantity of pore-forming material but also on its combustion characteristics, particle size distribution, residual ash content, clay mineralogy, and firing temperature. Optimizing these interacting variables remains essential for producing ceramic filters capable of maintaining satisfactory performance throughout their operational lifetime.

Overall, geological carbonaceous materials appear particularly promising because they combine relatively predictable thermal decomposition with more consistent chemical composition than many agricultural residues. However, experimental evidence remains limited, highlighting the need for systematic comparisons of lignite, coal fly ash, and conventional biomass pore formers under identical manufacturing conditions.

5.4 Influence of Pore Formers on Microbial Removal Performance

The primary objective of household ceramic water filters is the production of microbiologically safe drinking water. Consequently, microbial removal efficiency constitutes one of the most important performance indicators used to evaluate pore-forming materials. Unlike hydraulic conductivity or mechanical strength, microbial removal depends on the combined effects of pore structure, hydraulic residence time, filter thickness, and, in many cases, antimicrobial agents such as silver nanoparticles or colloidal silver coatings.

Physical removal of microorganisms occurs principally through size exclusion and tortuous flow pathways within the interconnected pore network generated during firing. Smaller pore diameters generally increase bacterial retention by reducing the likelihood of microorganism passage through the ceramic body. However, excessively small pores also reduce water flow rates, creating an inherent trade-off between filtration efficiency and productivity.

Among the reviewed studies, sawdust-based ceramic filters consistently demonstrated excellent microbial removal performance and remain the benchmark technology for household water treatment. Investigations by Oyanedel-Craver and Smith (2008), Brown and Sobsey (2010), van der Laan et al. (2014), and Rayner et al. (2017) collectively reported high bacterial removal efficiencies, particularly when ceramic filters were impregnated with colloidal silver. These studies established that optimized sawdust-derived pore networks provide an effective combination of hydraulic conductivity and microbial retention suitable for household applications.

Agricultural residues have likewise demonstrated favourable microbial removal performance. Nnaji and Adibe (2024) reported that ceramic filters fabricated using maize cob achieved bacterial removal efficiencies comparable to conventional sawdust filters despite slight differences in hydraulic performance. Rice husk-based filters also exhibited satisfactory microbial removal while benefiting from improved structural stability associated with silica-rich ash formation during firing. Nevertheless, relatively few comparative studies have evaluated multiple agricultural pore formers under identical production conditions, limiting direct assessment of their relative performance.

Most investigations involving starch, cellulose, and paper fibres have focused primarily on membrane permeability and structural characteristics rather than microbiological evaluation. Although these engineered pore formers produce highly uniform pore architectures, additional research is required to determine their long-term effectiveness in removing bacteria, viruses, and protozoa under realistic household operating conditions.

Evidence regarding geological carbonaceous materials remains particularly scarce. The study by Ayo et al. (2026) represents one of the first investigations demonstrating that low-rank lignite can produce ceramic water filters capable of achieving effective total coliform removal while maintaining acceptable water flow rates. Although encouraging, these findings require validation through additional independent studies involving broader ranges of pathogenic microorganisms and extended field evaluations.

An important observation across the reviewed literature is that microbial removal cannot be attributed solely to pore-forming materials. Filter thickness, firing temperature, clay mineralogy, pore size distribution, and antimicrobial silver application all contribute significantly to overall treatment performance. Consequently, future investigations should evaluate these interacting factors simultaneously to establish optimized ceramic filter designs capable of maximizing both microbial removal and hydraulic productivity.

5.5 Sustainability, Resource Availability, and Economic Considerations

Beyond filtration performance, the selection of an appropriate pore-forming material increasingly depends on sustainability, raw material availability, production cost, and environmental impact. These considerations have become particularly important in the development of household ceramic water filters intended for low- and middle-income countries, where affordable manufacturing and local resource utilization are essential for long-term adoption.

Wood-derived biomass has historically been the most widely used pore-forming material because of its low cost, widespread availability, and proven filtration performance. Sawdust, in particular, is readily obtained as a by-product of timber processing and requires minimal pre-treatment before incorporation into ceramic bodies. Its successful application in numerous household ceramic filter programmes has established it as the reference pore former against which alternative materials are commonly evaluated. However, increasing demand for biomass resources in energy production, construction, and agriculture has raised concerns regarding long-term availability and competition for raw materials in some regions.

Agricultural residues provide an attractive sustainable alternative because they convert crop wastes into valuable engineering materials while simultaneously reducing environmental pollution associated with open-field burning and waste disposal. Rice husk, maize cob, wheat bran, coffee residues, and similar by-products are generated in large quantities throughout agricultural economies and therefore represent inexpensive locally available resources for ceramic production. Their utilization supports circular economy principles by transforming agricultural waste into functional filtration materials. Nevertheless, considerable variability in moisture content, ash composition, particle size, and seasonal availability often results in inconsistent manufacturing performance and requires additional quality control during production.

Engineered organic additives such as starch and cellulose offer greater consistency because they possess relatively uniform chemical composition and controlled thermal decomposition characteristics. Consequently, ceramic membranes fabricated using these materials frequently exhibit more reproducible pore structures than those prepared from naturally occurring biomass. However, the higher cost of purified starches and cellulose fibres, together with their competing demand in food and industrial sectors, may limit their widespread application in low-cost household water filter manufacturing.

Geological carbonaceous materials represent a relatively unexplored but potentially valuable class of pore-forming materials. Unlike biomass-derived additives, lignite and coal fly ash are naturally abundant mineral resources or industrial by-products that are generally available throughout the year and exhibit comparatively stable physicochemical properties. Coal fly ash additionally provides significant environmental benefits through the beneficial utilization of industrial waste that would otherwise require disposal in landfills or ash ponds. Similarly, low-rank lignite possesses relatively predictable combustion characteristics that may permit more consistent pore development than heterogeneous agricultural residues.

From a circular economy perspective, the beneficial reuse of lignite and coal fly ash aligns closely with global efforts to reduce industrial waste generation while promoting sustainable material utilization. Numerous studies have demonstrated the successful incorporation of coal fly ash into ceramic membranes and porous ceramics, thereby reducing manufacturing costs while simultaneously minimizing environmental disposal problems. The recent introduction of lignite as a pore former further expands this approach by demonstrating that naturally occurring carbonaceous geological materials may also contribute to sustainable ceramic filter production.

Despite these advantages, the adoption of geological carbonaceous materials remains limited by the relatively small number of experimental investigations compared with conventional biomass pore formers. Consequently, available knowledge regarding long-term durability, environmental safety, combustion optimization, and microbial performance remains insufficient. Additional studies are therefore required before these materials can be widely recommended for household ceramic water filter manufacture.

Overall, the comparative evidence suggests that no single pore-forming material is universally superior. Wood-derived biomass remains the most thoroughly validated option for household ceramic water filters, agricultural residues provide highly sustainable waste valorization opportunities, engineered organic additives offer improved manufacturing consistency, and geological carbonaceous materials present an emerging alternative with considerable untapped potential. The optimal choice therefore depends on balancing filtration performance with local resource availability, manufacturing cost, environmental sustainability, and long-term material reliability.

The comparative characteristics of the major pore-forming material categories are summarized in **Table 5**, while the principal performance indicators employed throughout the reviewed studies are presented in **Table 6**.

Table 6. Performance Variables Used in the Review.

Performance Indicator	Importance
Porosity	Water permeability
Pore size distribution	Microbial retention
Water flow rate	Filter productivity
Hydraulic permeability	Ease of flow
Mechanical strength	Durability
Flexural strength	Crack resistance
Compressive strength	Structural integrity
Bulk density	Degree of pore development
Apparent density	Ceramic consolidation
Water absorption	Pore connectivity
Shrinkage	Dimensional stability
E. coli removal	Standard microbial indicator
Total coliform removal	Drinking water safety
Virus removal	Viral filtration performance
Turbidity removal	Physical filtration efficiency
Silver retention	Long-term antimicrobial performance

Table 7. Conceptual comparison of the major categories of pore-forming materials based on the collective findings of the reviewed literature. The ratings represent qualitative synthesis rather than direct quantitative comparisons.

Pore Former Category	Porosity	Flow Rate	Mechanical Strength	Cost	Sustainability	Research Maturity
Geological carbonaceous materials	High	High	High	Medium	Medium	Low
Wood-derived biomass	High	High	Moderate	Very Low	High	Very High
Agricultural residues	Moderate–High	Moderate	Moderate	Very Low	Very High	Moderate
Cellulosic additives	High	High	Low–Moderate	Moderate	High	Moderate
Starch-based additives	Moderate	Moderate	High	Low	High	High

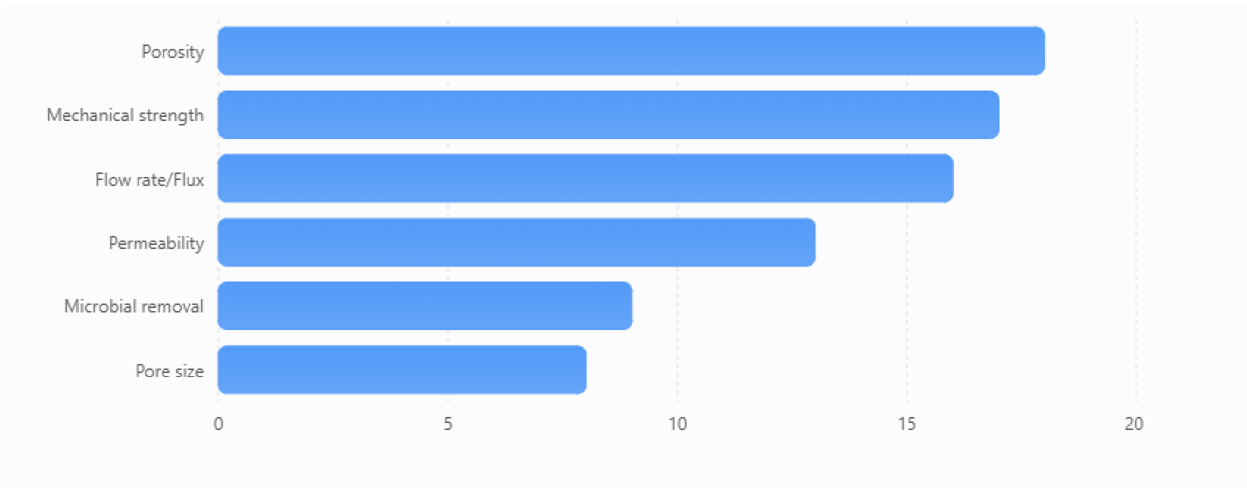

Figure 4. Frequency with which major performance indicators were evaluated across the reviewed studies. Porosity and mechanical strength were the most commonly reported parameters, whereas pore size and microbial removal were assessed less frequently.

6. Research Gaps and Future Research Directions

Despite considerable advances in the development of porous ceramic membranes and household ceramic water filters, several important knowledge gaps remain regarding the selection, optimization, and comparative evaluation of pore-forming materials. Most published studies have focused on improving individual performance characteristics, such as porosity, hydraulic conductivity, or microbial removal, rather than developing an integrated understanding of how different classes of pore formers influence the overall functionality of ceramic filtration systems. Consequently, meaningful comparisons across studies remain challenging because of substantial variations in raw materials, manufacturing procedures, firing conditions, and performance evaluation methods.

One of the most significant limitations identified in the reviewed literature is the overwhelming emphasis on biomass-derived pore formers, particularly sawdust and rice husk. While these materials have demonstrated satisfactory performance in numerous investigations, relatively little attention has been devoted to geological carbonaceous materials despite their potential advantages in terms of resource stability, predictable combustion behaviour, and year-round availability. As a result, current knowledge regarding the suitability of geological materials for ceramic water filter production remains limited.

Coal fly ash has received increasing attention as a ceramic raw material and membrane support additive because of its beneficial effects on ceramic densification, pore development, and waste valorization. However, most investigations involving coal fly ash have focused primarily on industrial ceramic membranes for wastewater treatment rather than household ceramic water filters intended for drinking water purification. Furthermore, many of these studies employed coal fly ash as a ceramic precursor rather than as the principal pore-forming material, limiting direct comparison with conventional biomass additives.

An even greater research gap exists for low-rank lignite. The available literature indicates that lignite possesses favourable combustion characteristics capable of generating interconnected pore networks during ceramic firing. Nevertheless, only a very limited number of experimental studies have investigated lignite as a pore-forming material for household ceramic water filters. Consequently, its influence on pore morphology, hydraulic performance, microbial removal efficiency, mechanical durability, and long-term operational stability remains insufficiently understood. Independent validation studies are therefore required before its broader application can be recommended.

Another important limitation concerns the absence of standardized experimental methodologies across published investigations. Considerable variations exist in clay mineralogy, particle size distribution, pore former concentration, firing temperature, sintering duration, silver application techniques, filter geometry, and performance testing protocols. These differences make quantitative comparison between studies difficult and hinder the development of universally applicable design recommendations. Establishing standardized testing procedures would greatly improve the comparability and reproducibility of future ceramic filter research.

The reviewed studies also reveal that relatively few investigations simultaneously evaluate hydraulic performance, mechanical properties, pore structure, and microbial removal within a single experimental framework. Most studies emphasize one or two performance indicators while neglecting others that are equally important for practical household applications. Future research should therefore adopt integrated multidisciplinary approaches that combine materials characterization, mechanical testing, hydraulic evaluation, microbiological assessment, and long-term field performance monitoring.

In addition, relatively limited attention has been given to the influence of pore-forming materials on long-term filter durability, repeated cleaning cycles, ageing behaviour, and sustained microbial removal under real household operating conditions. Laboratory studies often employ idealized water matrices and relatively short testing periods that may not accurately represent field performance. Extended field evaluations under diverse environmental conditions remain necessary to determine the long-term reliability of newly developed ceramic filter formulations.

From an environmental perspective, future studies should also investigate the life-cycle sustainability of alternative pore-forming materials, including their carbon footprint, energy requirements during firing, waste reduction potential, and economic feasibility. Such assessments are particularly important for developing countries where ceramic water filters are expected to provide affordable and environmentally sustainable household water treatment technologies.

Finally, advances in materials characterization techniques provide opportunities for significantly improving the understanding of pore formation mechanisms. Future investigations should integrate scanning electron microscopy (SEM), X-ray diffraction (XRD), mercury intrusion porosimetry (MIP), micro-computed tomography (micro-CT), Brunauer–Emmett–Teller (BET) surface area analysis, and image analysis methods to quantitatively relate pore morphology to filtration performance. Such integrated characterization would facilitate the rational design of ceramic filters with optimized hydraulic and microbiological properties.

Overall, the literature indicates that future ceramic water filter research should move beyond evaluating individual pore-forming materials in isolation and instead undertake systematic comparative investigations under standardized manufacturing conditions. Particular emphasis should be placed on geological carbonaceous materials, especially low-rank lignite, to determine whether their relatively uniform composition and predictable thermal behaviour can provide a viable alternative to conventional biomass-derived pore formers. Addressing these research gaps will improve scientific understanding of pore formation mechanisms while supporting the development of more efficient, durable, sustainable, and locally adaptable ceramic water filtration technologies.

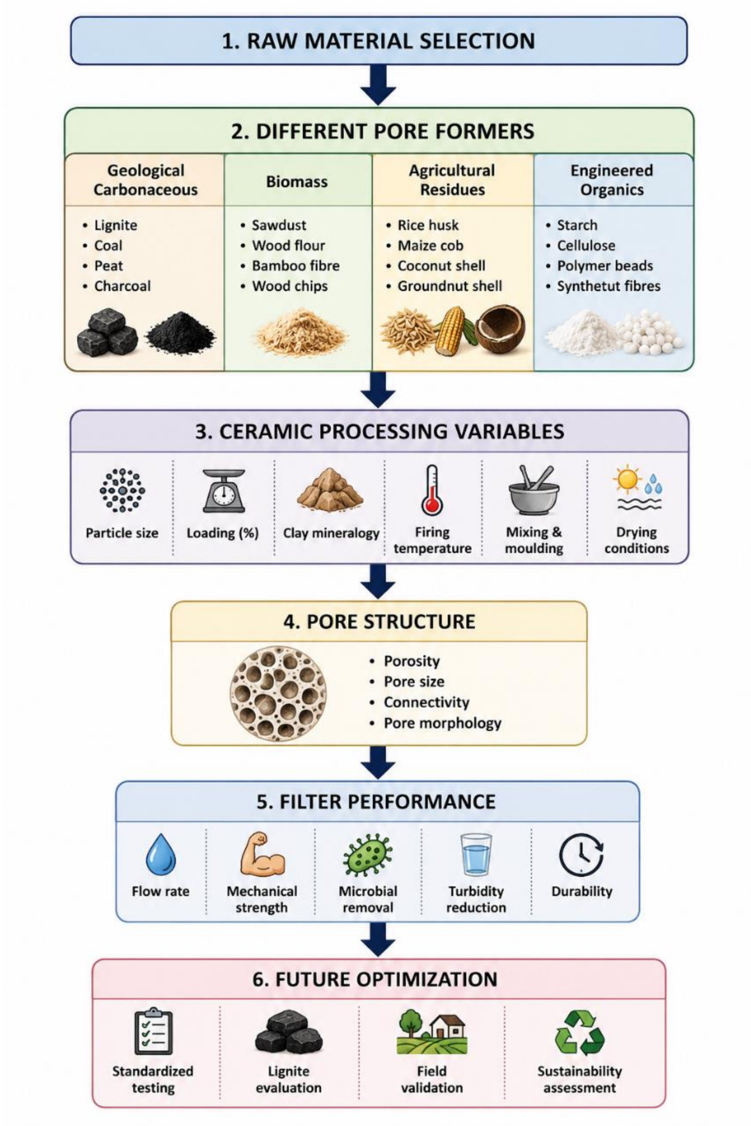

Figure 4. Proposed Future Research Framework.

CONCLUSIONS

This review critically evaluated the influence of pore-forming materials on the structural and filtration performance of ceramic water filters, with particular emphasis on geological carbonaceous materials as emerging alternatives to conventional biomass-derived pore formers. Twenty-one verified experimental studies, together with supporting review articles and seminal technical reports, were systematically synthesized to compare the effects of different pore-forming materials on pore development, hydraulic behaviour, mechanical strength, microbial removal efficiency, and overall filter performance.

The reviewed literature demonstrates that pore-forming materials play a decisive role in determining the microstructure and functional performance of ceramic filters. During firing, combustible additives generate interconnected pore networks that govern water permeability, pore size distribution, mechanical integrity, and microbial removal efficiency. However, the relationships among these properties are highly interdependent. Increasing pore former content generally enhances porosity and water flow but simultaneously reduces mechanical strength, requiring careful optimization of material composition and firing conditions.

Among the pore-forming materials reviewed, sawdust remains the most extensively investigated and widely adopted because of its proven effectiveness in household ceramic water filters. Agricultural residues, including rice husk, maize cob, wheat bran, and spent coffee grounds, provide sustainable alternatives that simultaneously promote waste valorization and circular resource utilization. Engineered organic additives such as starch, cellulose, and paper fibres offer improved control over pore architecture and manufacturing consistency but are generally less investigated for household drinking water applications.

A major contribution of this review is the comprehensive synthesis of geological carbonaceous pore formers, particularly coal fly ash and low-rank lignite. Although coal fly ash has been widely investigated for porous ceramic membranes and membrane supports, its application in household ceramic water filtration remains comparatively limited. More importantly, the available evidence indicates that low-rank lignite represents one of the least explored pore-forming materials despite its favourable combustion behaviour, relatively uniform composition, predictable pore generation, and year-round availability. The recent experimental study demonstrating the successful application of lignite in ceramic water filters provides encouraging evidence that geological carbonaceous materials may constitute a viable alternative to conventional biomass-derived pore formers.

The review also identified several important research gaps. Current studies employ highly variable raw materials, manufacturing procedures, firing schedules, and performance evaluation methods, making direct comparison between investigations difficult. Furthermore, relatively few studies simultaneously evaluate pore morphology, hydraulic performance, mechanical durability, microbial removal, and long-term operational behaviour under standardized experimental conditions. Comprehensive comparative investigations involving geological carbonaceous materials and conventional biomass pore formers remain particularly scarce.

Future research should therefore focus on standardized experimental comparisons of lignite, coal fly ash, sawdust, rice husk, maize cob, starch, cellulose, and other promising pore-forming materials using identical ceramic formulations and firing protocols. Advanced characterization techniques, including scanning electron microscopy, X-ray diffraction, micro-computed tomography, mercury intrusion porosimetry, and image analysis, should be integrated with hydraulic and microbiological testing to establish quantitative relationships between pore morphology and filter performance. Long-term field evaluations, life-cycle assessment, and techno-economic analyses will also be essential for determining the practical suitability of emerging pore-forming materials for household water treatment.

Overall, this review demonstrates that while biomass-derived pore formers continue to dominate ceramic water filter production, geological carbonaceous materials represent an underexplored research frontier with considerable scientific and practical potential. By providing the first comprehensive comparative synthesis of these materials within the context of household ceramic water filtration, this review establishes a foundation for future investigations aimed at developing more efficient, durable, sustainable, and locally adaptable ceramic filtration technologies for safe drinking water production.

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