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Review

Low-Cost Antibacterial Ceramic Water Filters for Decentralized Water Treatment: Advances and Practical Applications

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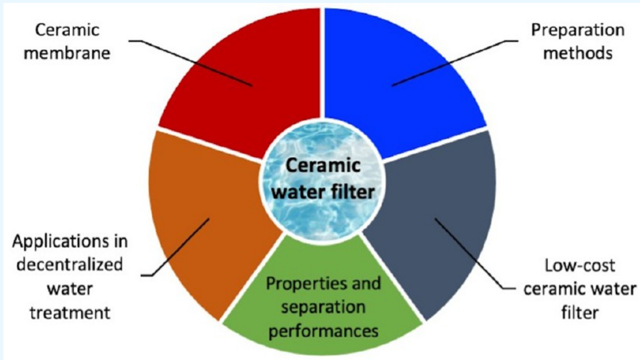
ABSTRACT: Access to clean water remains challenging for people living in underdeveloped regions, rural areas, and remote locations. In the absence of centralized water treatment systems, point-of-use (POU) solutions are necessary. Ceramic water filters (CWFs) have emerged as a practical and affordable option for decentralized water treatment. This review focuses on recent advances in antibacterial CWFs, including preparation methods, filtration performance, and applications. The review highlights the significance of preparation techniques, material choices, and additives in determining CWF properties and performance. Despite virus and chemical contaminant removal limitations, ongoing research on nanofillers and antibacterial additives shows promise for enhancing the CWF performance. The cost-effectiveness, ease of production, and low operational requirements of CWF make it a viable solution for decentralized drinking water systems, particularly in resource-limited areas. Studies have demonstrated the efficacy of CWFs in reducing water contaminants, but proper maintenance and user training are crucial to optimal performance.



1. INTRODUCTION

People living in underdeveloped regions, rural areas, and remote locations still face the challenge of obtaining clean water for daily consumption. A centralized water treatment system is often unavailable in these areas, making a point-of-use (POU) system a viable solution.[1−3] POU systems should be easy to operate, low cost, and effective in removing contaminants and pathogens. One such technology that has been found to be practical and sustainable is the ceramic water filter (CWF).[4−6]

A CWF is a porous filter made from clay and sieve materials.[7−10] CWFs are made from a combination of clay, water, and combustible materials like sawdust or rice husks.[11] The sieve materials could be sand, sawdust, or other burnout materials.[12] These materials are mixed with clay and fired at high temperatures to create a porous structure. The porous structure of ceramic water filters allows for the filtration of contaminants and pathogens in the water. The filtration is driven by gravity, requiring relatively low or no energy input.[13] The filtration process occurs through size exclusion, sedimentation, and adsorption mechanisms.[14−16] In addition to its ability to remove turbidity and pathogens, the CWF can produce clear water without changing the flavor or odor of the water. CWF can be fabricated in different geometries, making it flexible for various conditions.[17−19] Another advantage of a CWF is its service life of up to 5 years, making it an affordable option for decentralized POU systems.[20]

However, CWF has some limitations, such as low productivity or flux and a low removal rate for viruses and chemical contaminants. To address these limitations, many studies have been dedicated to improving the virus removal rate of CWF by introducing nanofillers, such as silver, into the filter (Figure 1a,b). CWFs with nanofillers have been found to have effective removal of viruses and antibacterial properties. This has led to an increase in the amount of research in this field.

Figure 1a illustrates the distribution of publications pertaining to the subject of "ceramic water filter" throughout multiple years. The chronological analysis reveals a solitary entry in 1985, followed by a conspicuous hiatus until the early 2000s, at which point research in this area commences gaining momentum. The frequency of published works remains relatively moderate, fluctuating between one and four publications per year until 2010. Subsequently, a discernible surge is observed, with the number of publications oscillating between four and fifteen each year. Notably, the pinnacle year

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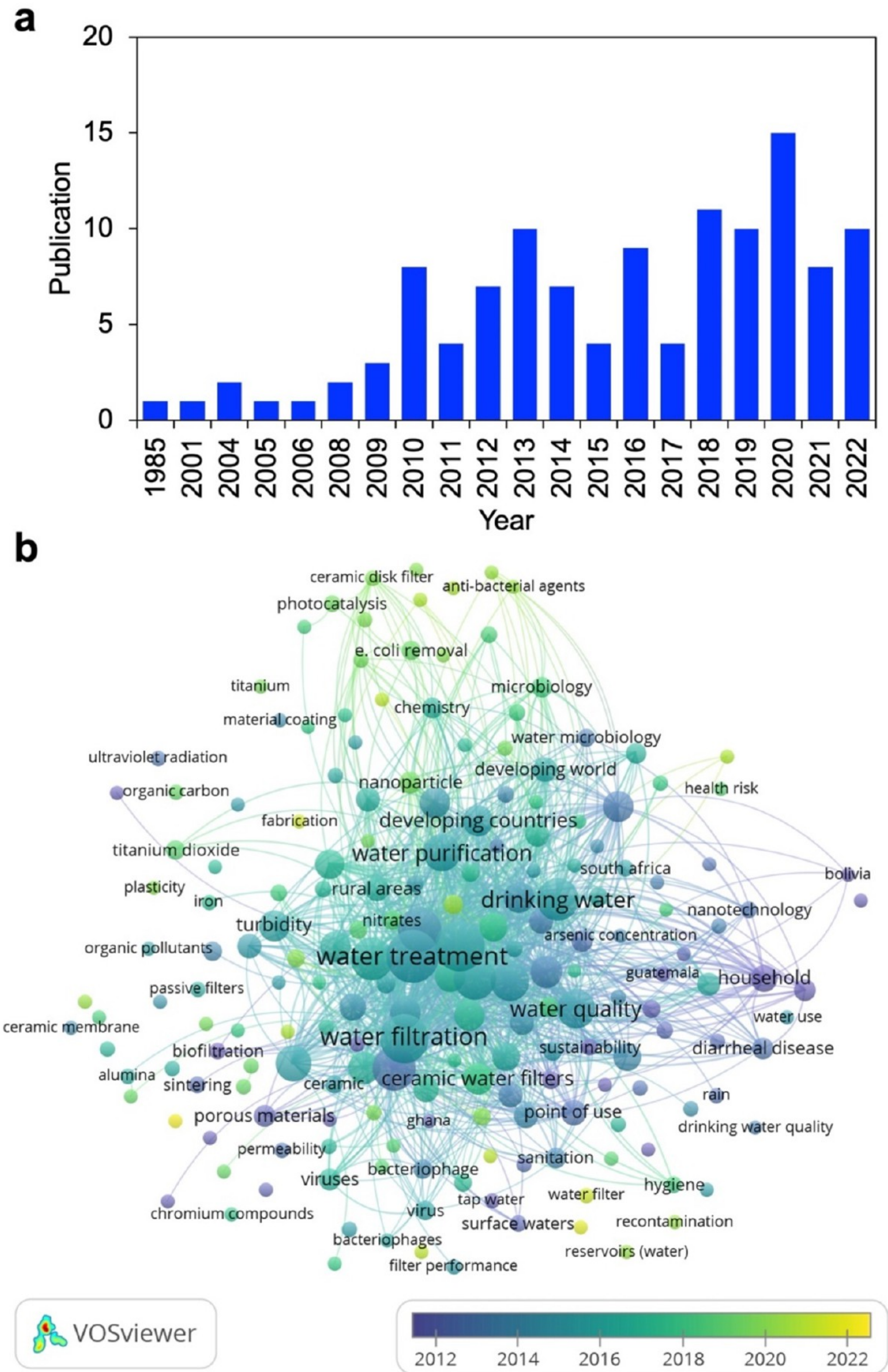

Figure 1. (a) Ceramic water filter (CWF) publications per year indexed by Scopus (accessed on November 14th, 2022, with search queries: TITLE-ABS-KEY(terms)). (b) Network visualization of CWF keyword analysis constructed by using VOSviewer software.

for publications appears to be 2020, indicating heightened scholarly interest and potentially the emergence of technological advancements during that time frame. Although the data encompass the period from 1985 to 2022, most research efforts have been concentrated within the past two decades, underscoring the growing significance accorded to ceramic water filter technology and its diverse applications.

The bibliographic network (Figure 1b) illustrates a decade-long investigation into the study of ceramic water filters, which revolves around central themes, such as "water treatment", "water purification", and "water filtration". The focus on materials and technologies is apparent through "ceramic membrane" and "nanotechnology". At the same time, the significance of microbial safety is underscored by terms like "*E. coli* removal" and "water microbiology". The network also emphasizes the global context by referring to "developing countries" and specific regions, indicating the importance of ceramic filters in addressing water quality challenges in various socioeconomic settings. Furthermore, broader considerations related to the environment and health, such as "sustainability" and "diarrheal disease", are featured, along with insights into practical applications through elements like "household" and

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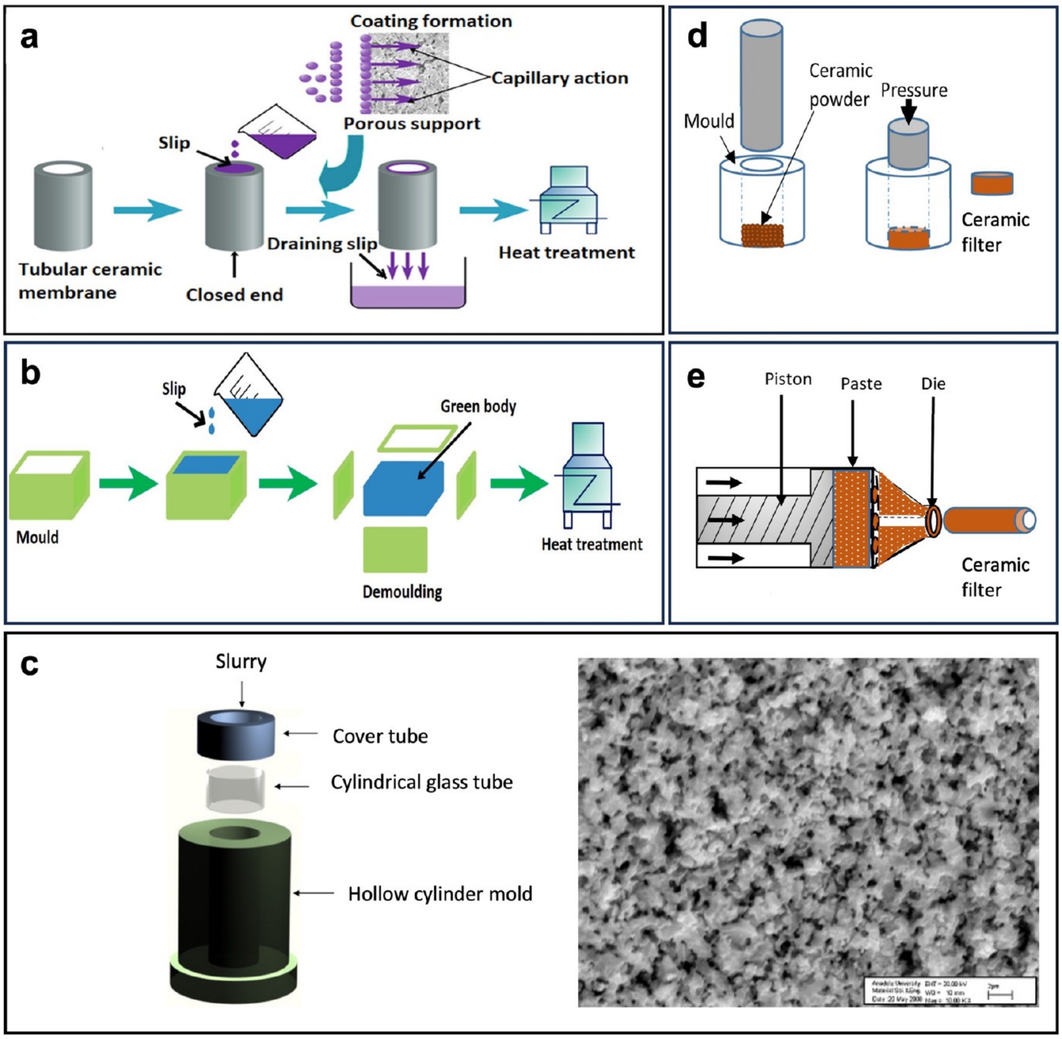

Figure 2. Preparation methods of ceramic water filter: (a) preparation of tubular and (b) flat membranes. Reprinted with permission from ref 36. Copyright 2022, Elsevier. (c) Multilayer tubular ceramic membrane and scanning electron microscopy image of the filter. Reprinted with permission from ref 30. Copyright 2020, Elsevier. (d) Pressing method. (e) Extrusion method. (d) and (e) are reprinted with permission from ref 37. Copyright 2021, The Authors (under a creative common license, https://creativecommons.org/licenses/by-nc-nd/4.0).

Table 1. . CWF Fabrication Methods

fabrication method	description	advantages	example applications	refs
slip casting	a slurry mix is poured into a mold and left to dry, taking the shape of the mold	simple process, consistent porosity, and particle retention	mass production and creating flat or complex shapes; used with materials like kaolin, rice husk, and zeolite	24, 25, 28−31
pressing	a solid mixture of clay and other materials is compressed in a mold to form the filter	eliminates the need for liquid slip, suitable for dry mixtures	used for making filters with specific materials like Redart clay and sawdust powder	38
extrusion	the material is forced through a die of a desired shape, optimizing the production of filters with controlled pore morphology	enhances quality and uniformity of porous materials, precise control over porosity	porous Al_2O_3 ceramic filters with controlled pore structure for reducing alloy casting defects	39
hand molding	materials are shaped by hand into molds after mixing with additives	allows for careful shaping and customization, hands-on approach	diatomite-based porous ceramic filters with desired porosity and structural integrity	40

"tap water". All in all, this intricate visual representation demonstrates the multidimensional nature of research on ceramic water filters, combining the fields of materials science and global health implications.

In recent years, numerous pertinent investigations have contributed to the comprehension of CWFs. Yang et al. have presented in their work a comprehensive exploration of vital factors influencing the performance of CWFs.[21] This study tackles the challenges associated with filter flow rates, efficiency in removing bacteria, and the eradication of specific pollutants. On the other hand, Venis and Basu[22] narrowed their examination, focusing on the role of silver in CWFs. They conducted a thorough review on its effectiveness in disinfection and different methods of application. At the same time, Shepard and Oyanedel-Craver[23] published an extensive analysis, delving into the inconsistencies in testing and discussing the potential standardization of CWF testing protocols. They placed emphasis on the influence of

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Table 2. . CWF Materials, Preparation Methods, and Performances

preparation methods	materials	sintering/ firing (°C)	pore size (μm); porosity	performance[a]	ref
Slip-casting	kaolin, rice husk, zeolite	T = 1200	porosity 24.6%	flux 13 L m^{-2} h^{-1} (at 2 bar), textile dye removal 75.5%	27
slip-casting	China clay, ball clay, limestone, diatomaceous earth	T = 1100	pore size 0.2−0.5 μm	microbial removal efficiency 99.99%, apparent porosity 60−70%	41
slip-casting	porcelanite rocks and kaolin clay	T = 700	porosity 48%	pentachlorophenol removal 97.57%	42
pressing	clay and sieved sawdust (50:50 v/v)	T = 950	pore size 1.07 ± 0.05 μm	*E. coli* removal 99.998%, LRV of *E. coli* 4.46 ± 0.15, permeability 1.16 × 10^{-14} m^2	43
pressing	red clay and combustible materials (paper or tree leaves) (4:1 w/w) + lanthanum coating	T = 1000	pore size 0.2−20 μm	*E. coli* removal >99.9999%, LRV of *E. coli* >6	44
pressing	clay and combustible materials (e.g., sawdust and eragrostis tef husk)	T = 900	porosity 32−43%	turbidity reduced from 13 NTU to 1.15−0.45 NTU, total coliform removal 99.64%, LRV of total coliform 3	45
pressing	clay and macadamia nutshell	T = 900	porosity 9−23%, pore size 1.5−1.7 nm	flux 289 L m^{-2} h^{-1} (at 13.8 kPa), methyl orange removal 40%, turbidity removal 95−98%, chromium(III) removal 40%, lead(II) removal 71%	46
pressing	kaolin, bentonite clays, and sawdust	T = 800	porosity 40−44%	turbidity removal 99.7%, TSS removal >94%	47

[a]LRV denotes the log reduction value.

manufacturing and testing conditions on the performance of CWFs. This review focuses on recent advances in antibacterial CWFs, including preparation methods, filtration performances, and applications. We will start by discussing CWF preparation methods and the introduction of antibacterial additives. We will then move on to discuss low-cost CWFs and ceramic membranes, separation performance, and antibacterial properties of CWFs. This review will also cover applications of CWFs in decentralized water treatment systems. Finally, this review provides future outlooks and research directions for CWF.

2. CWF PREPARATION METHODS

2.1. Preparation of CWF. Several methods, such as slip casting, extrusion or pressing, and hand molding are generally used to fabricate CWFs[24] (Figure 2 and Tables 1 and 2). However, slip casting is the most commonly used method due to its simplicity and ability to produce filters with consistent porosity and particle retention properties.[25] Extrusion and hand-molding methods are typically used for small-scale production or when specific filter geometries are required.[26]

The process of slip casting begins with the deposition of the ceramic slip into a specifically tailored mold, where it is allowed to solidify over a designated time frame. The mold's walls absorb the surplus moisture, thereby expediting the solidification of the slip. Upon the drying of the slip, the mold is detached, resulting in an exact duplicate of the mold's shape (refer to Figure 2a). This technique is also applicable to the production of flat filters. In this case, the ceramic material is cast in a planar configuration and undergoes drying and sintering processes, leading to the creation of a flat ceramic filter (Figure 2b). For instance, the slip-casting technique has been utilized in manufacturing ceramic water filters, as referenced in ref 27, using kaolin, rice husk, and zeolite as the primary materials. First, kaolin, rice husk, and zeolite are sieved to achieve a particle size of 25 μm for kaolin and 50 μm for rice husk and zeolite. Subsequently, additives and kaolin are mixed using a ball mill for 4−5 h. The mixture of kaolin, additives, and water, formulated with specific proportions (in the form of a slurry), is poured into a mold and left in room conditions for 1 day. The formed ceramic filter is then extracted from the mold and subjected to sintering at a temperature of 1200 °C. The sintering process is carried out for 2 h, with a heating and cooling rate of 2 °C per minute.

Slip casting has been effectively utilized to fabricate ceramic filters with specific pore structures, as evidenced by a study that utilized diatomaceous earth to achieve a pore size of less than 1 μm. This optimization enhanced microbial removal efficiency and improved water flow rates.[28] Similarly, investigations into green ceramic water filters have incorporated rice husk and zeolite-based rice husk ash as additives within a kaolin-based matrix. Slip casting was employed due to its simplicity and ability to create filters with high porosity and satisfactory performance in removing textile dyes.[29] Furthermore, the migration of fine particles inherent to slip casting has facilitated the production of multilayer glassy ceramic filters. By strategically altering the pore sizes in different layers, these filters can provide tailored filtration capabilities.[30] Even in gas separation, the slip-casting method has been adapted into a vacuum-assisted technique to fabricate thin carbon-zeolite composite membranes on ceramic supports (Figure 2c). Figure 2c (right) displays the vitreous microstructure of the filter. The micrograph effectively demonstrates the grain coating phenomenon, whereby grains with a higher atomic number are depicted as white, indicating the presence of lead-containing glass uniformly distributed throughout the microstructure.[31] This unique and compact microstructure, consisting of multiple layers, holds significant potential for advancing capillary ceramic filters with enhanced efficiency.[31] This adaptation showcases the versatility of slip casting beyond traditional ceramic processing.

It is pertinent to consider the potential of three-dimensional (3D) printing technology in revolutionizing the fabrication of CWFs.[32−35] This advanced manufacturing approach offers a paradigm shift in filter production for water treatment, potentially addressing specific and localized contamination challenges with rapid, on-site production capabilities. The agility of 3D printing allows for creating filters customized to the unique needs of diverse settings, ranging from remote communities to critical infrastructure sites. This could be especially pivotal in responding swiftly to acute water contamination incidents, thereby mitigating adverse health impacts and disruptions to the water supply.

Ceramic water filters can be prepared by using the pressing technique, which involves compressing a mixture of clay and other materials into a mold to get the desired shape and structure. Subsequently, the filter was removed from the mold and prepared for drying and firing. Unlike slip-casting, where a

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liquid clay mixture called a slip is poured into a mold and solidified through drying and firing, pressing eliminates the need for a liquid slip by directly compressing a solid mixture into the mold. For instance, the application of pressing techniques for ceramic water filter fabrication has been reported by Omoniyi et al.[38] This study employed Redart clay and sawdust powder consisting of 75% oak and 25% Spanish cedar as the materials. The sawdust powder was sifted by using a 35-mesh screen, and the sifted clay and sawdust were mixed in a mixer with periodic additions of deionized water. The mixture was mixed until it formed large lumps and was then manually shaped before being placed in molds in a hydraulic press machine. A pressure of 140 kPa was applied to the mold by using a 50-ton hydraulic press machine to compress the filter. Following compression, the filter was air-dried for 6 days at a room temperature of 25 °C and a relative humidity of 40%. Subsequently, the air-dried ceramic water filter was fired in a gas kiln. It was gradually heated to a temperature range of 450−550 °C over 3 h (at 50 °C/h) to eliminate the combustible sawdust. The heating process was then continued at a rate of 100 °C per hour until the desired sintering temperature (850, 900, and 950 °C) was reached for 5 h. Finally, the filter was cooled to room temperature.

The application of an extrusion technique for the production of ceramic filters has been demonstrated to significantly enhance the quality and uniformity of porous filtration materials. According to the findings presented in ref 39, a sophisticated layered extrusion forming method was utilized to fabricate porous Al_2O_3 ceramic filters with precise management of pore morphology. The investigation meticulously optimized the extrusion variables, which encompassed the filling rate, nozzle diameter, and filling angles through the implementation of orthogonal experiments and response surface analysis. The sintering process was also finely adjusted, with the optimum temperature determined to be 1400 °C, in order to ensure the filters possessed the desired specifications in terms of robustness and porosity. The extrusion technique exhibited effectiveness in generating filters that possessed a flexural strength of 14.35 MPa, a high total porosity of 67.6%, with 53.40% of this being macroporosity, and a negligible linear shrinkage rate of 2.51%. These optimized conditions culminated in a highly controlled manufacturing process, resulting in ceramic filters that exhibit exceptional performance in the reduction of alloy casting defects.

In the research carried out by Shen et al., the method of hand compression molding was utilized to create diatomite-based porous ceramic filters.[40] This precise procedure involved a sequence of meticulous stages that were crucial in order to attain the desired porosity and structural integrity.[40] Initially, the diatomite underwent a thorough washing and filtering process, followed by a calcination process at a temperature of 550 °C, which enhanced its properties. Subsequently, the resulting material was combined with sodium carbonate and an aqueous solution containing polyacrylamide as a dispersant, as well as poly(vinyl alcohol), which served the dual purpose of being a binder and pore-forming agent. The homogeneous slurry produced from this mixture was carefully shaped into consistent cylindrical forms through the meticulous process of hand molding, thereby exemplifying the hands-on nature of this methodology. These samples were then systematically dried at a temperature of 60 °C and sintered of the dried ceramics, which took place at temperatures ranging from 600 to 1000 °C, leading to the solidification of a highly porous matrix. By optimization of the sintering temperature and the quantities of additives in a controlled experiment, the optimal mixture was identified to yield ceramics exhibiting a porosity of 71.74%. Furthermore, these ceramics demonstrated a compressive strength of 4.535 MPa, an average pore diameter of 10.023 μm, and a substantial specific surface area of 230 m^2/g. Comprised primarily of tetragonal cristobalite, these ceramics showcased an impressive decoloration rate of 40.43% for methyl orange within 90 min, indicating their efficacious adsorption capabilities.

2.2. Impact of Materials on CWFs. The plasticity of clay minerals plays a crucial role in determining the properties of CWFs, especially in pressing and extrusion methods. In a reported study,[48] the plasticity indices were determined using the Atterberg limits. The clays analyzed in the study were identified as aluminosilicates with SiO_2/Al_2O_3 ratios ranging from 1.61 to 3.03 and plastic indices ranging from 8 to 49. When dealing with clays that exhibit low plasticity, the addition of plasticizers is necessary to bind the particles together. Alternatively, working with the optimum moisture content can help extend the plastic regions. Achieving good plasticity is essential to ensure that the material does not show early cracking or extreme sensitivity to humidity. To obtain a balanced plasticity that can withstand the frothing pressure during backwashing in treatment plants or when using Expanded Clay Aggregates in water bottles, it is common practice to combine low-plastic clay with high-plastic clay.[48]

Combustible materials play a significant role in the production of ceramic water filters. Experimental results demonstrate their influence, which includes increased water plasticity, higher shrinkage rates, and filter porosity.[45] Incorporating combustible materials at higher loading enhances water plasticity, necessitating greater water mixing for optimal pellet workability. Test pellets containing more combustible materials exhibit increased shrinkage following the firing process, encompassing linear drying shrinkage (ranging from 1.25% to 3.25%) and total shrinkage. By firing at a temperature of 900 °C for 2 h, complete combustion of the combustible materials is ensured, resulting in sufficient pores within the filter structure. However, in the case of CPWF with *Eragrostis tef* husk, some residues may persist despite the combustion process.[45] The research findings, comparing combustible materials such as sawdust, maize cob, and cassava, revealed that sawdust produced the most optimal porosity.[49] As a result, they achieved the highest flow rate of filtered water. The high porosity of the filter plays a crucial role, as it allows water to pass through easily while efficiently removing impurities.

2.3. Impact of Fabrication Conditions on CWF. During the pressing process, the compression pressure is a crucial parameter. For instance, compression pressure has an impact on the filter's porosity.[46] The study[46] revealed that the filter's porosity decreased from 23% to 9% when the compression pressure was increased from 2.5 to 15 MPa. This reduction in porosity is attributed to the compaction of the clay material.[46] Consequently, optimizing the appropriate compression pressure to achieve the desired porosity of the filter is essential.

Sintering is an important step, as it can determine filter properties. The sintering process can affect the porosity and pore size of the filter as well as improve its mechanical strength. Results of a study[43] demonstrate that the sintering temperature plays a crucial role in influencing the filter average pore size and porosity (Figure 3a,b). Elevating the sintering

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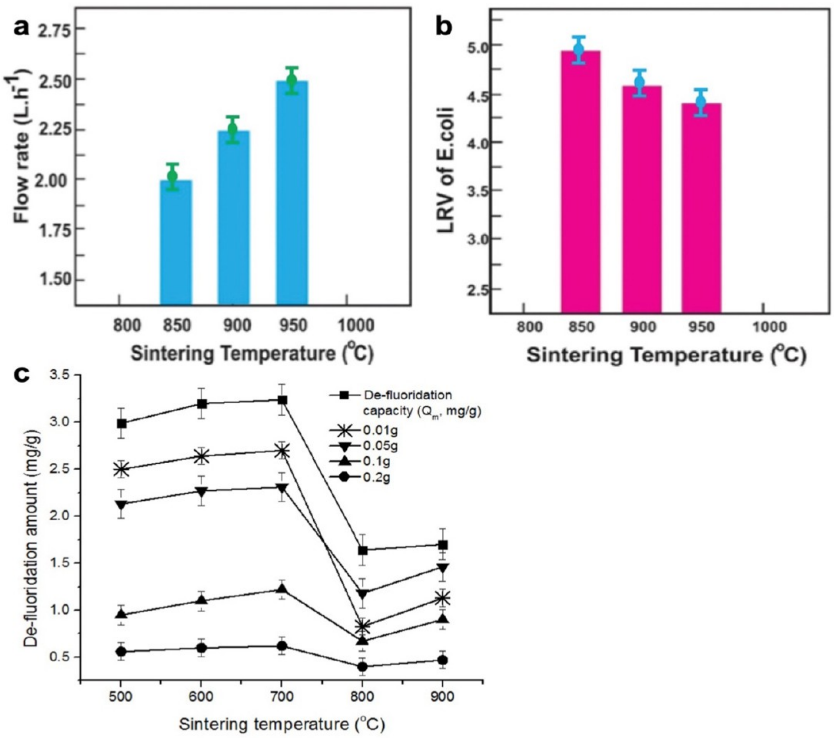

Figure 3. Effect of sintering temperature. (a) Filtrate flow rate. (b) *E. coli* removal. (a) and (b) are reprinted from ref 43. Copyright 2022, The Authors. Under a creative Creative Commons CC BY license. (c) Fluoride adsorbed by CWF Reprinted with permission from ref 50. Copyright 2022, Elsevier.

Table 3. . Additive Introduction into CWFs

antibacterial agent	method	important features	ref
lanthanum(III)	impregnation	As(V) adsorption capacity 24.8 mg/g, As(III) adsorption capacity 10.9 mg/g, LRV of *E. coli* >6 (>99.9999% removal).	44
Ag nanoparticles	impregnation	100% bacterial removal	49
Ag nanoparticles	coating[a]	LRV of *E. coli* 10.9	59
Ag	in situ reduction of $AgNO_3$	*E. coli* and coliform removal 100%	54
Ag	in situ reduction of $AgNO_3$	LRV of *E. coli* 4.11, LRV of total coliform 4.06	18
Ag/Zn	impregnation	LRV of *E. coli* 3.1	60
Ag/ZnO	painting	LRV of *E. coli* 3.73	55
Ag	in situ reduction of $AgNO_3$	total coliform removal 89–96%, *E. coli* removal 99–100%	61
Cu	in situ reduction of $Cu(NO_3)_2$	LRV of *E. coli* 3.54, LRV of total coliform 3.33	18
graphitic carbon nitride (g-C_3N_4)	drop-casting	LRV of bacteria (*E. coli* and total coliform) ~7	52
Mg/Ca phosphate	in situ synthesis	fluoride adsorption capacity 2.6 ± 0.3 mg/g	50
hydroxyapatite	blending	LRV of *E. coli* 4.91, LRV of fluoride 2.56	53
hydroxyapatite and alumina	blending	LRV of bacteria 4.69, LRV of MS2 virus 2.26, LRV of fluoride 3.47	16
bone particle	blending	LRV of *E. coli* 4.89, LRV of fluoride 3.28	53
iron oxide-biochar	blending	fluoride removal 92.5–94.7%	58
nano-CeO_2	painting/brushing	arsenic removal 84.58%	56
ZnO nanoparticles	brushing	LRV of *E. coli* >2.5	57

[a]A detailed procedure was not explained.

temperature from 850 to 950 °C significantly increased the average pore size, expanding it from 0.73 to 1.07 μm. Furthermore, the average porosity of the filter exhibited notable enhancement, from 35.38% to 43.90%. In addition, the compressive strength of the filter showed an increase from 6.55 to 7.02 MPa with increasing sintering temperature from 850 to 950 °C. Higher sintering temperatures result in an increased level of CWF crystallinity.[50] Elevated temperatures experienced during the sintering process induce an increase in the degree of crystallinity observed in CWFs.[50] This phenomenon arises from modifications in the phases present and growth in the dimensions of the crystal structures. The spectroscopy analysis reveals the replacement of less crystalline materials with more crystalline phases, specifically β-tricalcium phos-

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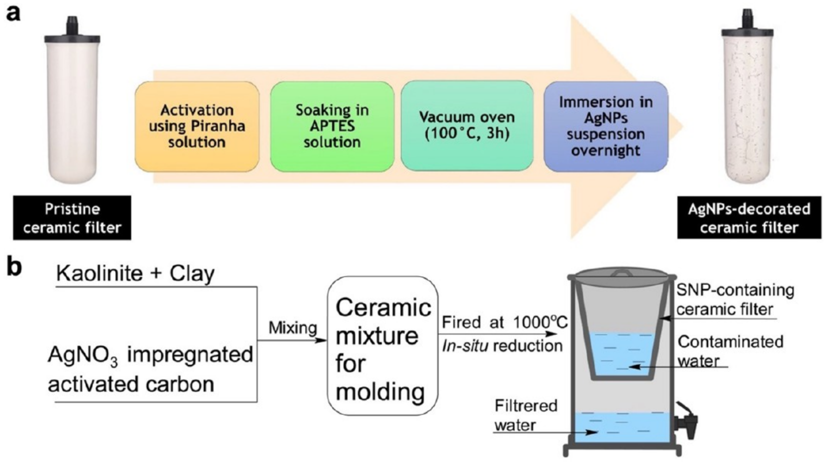

Figure 4. Introduction of silver nanoparticles into the CWF. (a) Ag nanoparticles impregnation (reprinted from ref 49. Copyright 2023, The Authors. Under a Creative Common license, http://creativecommons.org/licenses/by/4.0). (b) Activated carbon impregnation with $AgNO_3$ followed by in situ reduction of silver nanoparticles in CWF.[54] Copyright 2019, Elsevier.

phate (β-TCP), indicating a denser and more organized mineral lattice. This fact was further supported by the pair distribution function analysis, where an increase in the size of the crystallites was found to be directly proportional to the higher level of crystallinity at elevated temperatures.[50]

In the case of CWF modified with calcium/magnesium phosphate, the CWF sintered at 700 °C showed better defluoridation performance compared to 500 °C, possibly due to the formation of improved defluoridating agents such as metal oxides (calcium oxide and magnesium oxide) and β-tricalcium phosphate (β-TCP).[50] However, at higher sintering temperatures, specifically 800 °C, the filter's performance decreased, likely due to crystallization domination, agglomeration, and reduced surface area.[50] The example of sintering temperature effect on defluorination performance is depicted in Figure 3c.

2.4. Introduction of Additives to CWFs. Ceramic water filters can be enhanced with additives to improve their separation properties and antibacterial activities. Additives can be incorporated into ceramic water filters using various methods (Table 3 and Figure 4). One method is wet impregnation. For example, ceramic water filters can be coated with lanthanum using this method.[44,51] In this process, the ceramic water filter is immersed in a solution of $La(NO_3)_3$ at a specific concentration and then heated at 385 °C for 3 h. Afterward, the filter is cooled to room temperature and rinsed. This method can produce a sufficiently effective coating of the filter.

The impregnation method has been utilized for the modification of ceramic water filters with silver nanoparticles, as described in ref 49. To initiate the impregnation process, the ceramic water filter is first activated using a hot piranha solution (1:3 v/v, 30% H_2O_2/98% H_2SO_4). Subsequently, the filter is treated with a 2% ethanol solution of APTES, which introduces amino groups onto the surface. Following APTES treatment, the activated filter is immersed in a solution containing AgNPs overnight. This allowed for the effective coating of silver onto the ceramic water filter. After impregnation, the filter is thoroughly washed with ethanol to remove any unbound AgNPs and left to air-dry. Although this method demonstrates successful silver coating on the ceramic water filter, it should be noted that there is still a slightly observed dissolution of silver, albeit insignificant (33 μg/L for 3 months).

Another method that has been used to add additives to the CWF is drop-casting. The drop-casting method has been employed to immobilize modified graphitic carbon nitride (MCN) onto the filter surface.[52] This method prepares a coating suspension by dispersing MCN in a mixture of water and ethanol (containing 25% ethanol). Subsequently, this coating suspension is dropped onto the filter surface and dried in an oven at 40 °C for 12 h. Afterward, ceramic water is finally prepared for further experiments.[52] This method successfully coats the CWF, leading to notable surface morphology and chemical composition alterations. The MCN-coated surface exhibits a rougher and denser texture compared to the original, untreated filter surface. In addition, the CWF with MCN also exhibits higher antibacterial photocatalytic activity compared to the pure ceramic filter.[52]

The additive can also be introduced using an in situ synthesis method, as mentioned in the modification of CWF with Ca/Mg-phosphate.[50] Preparing the clay ceramic adsorbent materials involves introducing dolostone as a source of calcium and magnesium cations. It is essential to add dolostone in a specific ratio to the clay. After thoroughly mixing, shaping, and drying the mixture, the filters are then sintered at a specific temperature.[50]

One relatively simple method of additive incorporation is blending or direct mixing. Additives are added to the filter material mixture, and the filter manufacturing process continues. This method was used to create filters by adding hydroxyapatite and bone particles.[53] Although the procedure is relatively simple, the additives can be distributed evenly throughout the filter matrix.

Another simple technique that has been employed to modify CWFs is painting. This method has been utilized to modify CWFs with Ag/ZnO.[55] Ag/ZnO nanocomposite powders were dispersed in deionized water and subjected to ultrasonic treatment for 5 min, after which they were applied to the upper surface of the CWF. Results of the study showed that the Ag/ZnO nanocomposite was distributed on the upper surface of the CWF, with the highest concentration observed within a depth of less than 1 mm from the surface.[55] The painting or brushing method was also employed to deposit nano-CeO_2 on

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the surface of the filter.[56] This method effectively deposited nano-CeO_2 evenly on the filter surface, and no nano-CeO_2 particles were detected in the effluent.

Incorporating additives into the manufacturing process of CWFs has proven to be a significant advancement in augmenting their efficacy. Incorporating nano-ZnO into ceramic water disk filters significantly improves their performance, particularly in removing *E. coli* from water.[57] This enhancement is attributed to the filter's retention capabilities and the photocatalytic antibacterial activity of nano-ZnO. Factorial analysis identified pore size as the most significant factor affecting *E. coli* removal efficiency, while clay content primarily influenced the flow rate of the modified filters.

Doping of hydroxyapatite within CWFs has been shown to significantly impact their operational efficacy, particularly regarding eliminating fluoride and bacteria in tainted water sources.[53] Hydroxyapatite, in conjunction with clay and meticulously sieved sawdust within CWFs and subsequently sintering them at either 850 or 900 °C contributes to the fabrication of micro/nanoporous architectures. These intricate structures are imperative for the geometric entrapment of microbial pathogens and fluoride adsorption.

Including a composite of iron oxide-biochar (FBC) in CWFs dramatically enhances their effectiveness in eliminating fluoride from potable water.[58] The investigation revealed that the CWF embellished with a mixture of 10% FBC (C85:S5:B10) displayed the highest efficiency in fluoride removal. For synthetic water with an initial fluoride concentration of 15 mg/L, the elimination of fluoride reached 92.5% ± 0.7%, while for actual groundwater with an initial fluoride concentration of 9 mg/L, the removal efficiency rose to 94.71% ± 0.79%. These findings exceeded the fluoride removal efficiencies of CFs with a lower FBC content (C85:S10:B5 and C85:S15). Furthermore, the C85:S5:B10 arrangement effectively lowered the fluoride concentrations in both natural and synthetic water to levels below the recommended limit of 1.5 mg/L set by the World Health Organization. As time progressed, the fluoride removal capacity of all CFs decreased, but C85:S5:B10 maintained its efficiency for a longer duration, treating a larger volume of water containing fluoride (150 mL) in comparison to the other two types of CFs (100 mL each). This exceptional performance can be attributed to the higher content of FBC in C85:S5:B10, which augments the number of active sites for fluoride removal.

Incorporation of nano-CeO_2 into CWFs (CF-CeO_2) significantly enhances arsenic removal efficiency, increasing from 64.04% to 84.58% with a coating increase from 0.10 to 1.00 g of nano-CeO_2.[56] This enhancement, however, results in a reduced flow rate due to the nano-CeO_2 coating obstructing the filter pores. Optimal performance is achieved with a 1.00 g coating, balancing efficiency and flow rate. The arsenic removal efficiency of CF-CeO_2 is also influenced by aqueous conditions such as influent arsenic concentration, pH, and background electrolyte concentration. Under low to moderate pH levels, the filters maintain high efficiency (above 80%, slightly decreasing from 97.23% to 96.62% in acidic conditions). The removal mechanisms predominantly involve ligand exchange and electrostatic attraction, with the specific adsorption process being relatively insensitive to changes in ionic strength, as evidenced by the negligible impact on As(V) removal efficiency with up to a 100-fold increase in background electrolyte concentration. This indicates that specific adsorption is the primary force driving the As(V) removal in CF-CeO_2.

Incorporating a lanthanum (La) coating on CWFs markedly enhances their bacterial removal efficiency, flux, and stability.[44] Experimental analyses reveal that La-coated CWFs, especially those treated at 400 °C, exhibit significantly higher *E. coli* log removal values (LRVs) compared to uncoated counterparts, surpassing traditional silver-impregnated filters in efficacy. This enhancement is attributed to the La coating altering the filter's surface properties, increasing density while reducing porosity and surface area, thus improving bacterial cell immobilization. The concentration of La in the coating process directly influences the bacterial removal efficiency, with higher concentrations leading to more significant La deposition and enhanced performance. Long-term filtration experiments demonstrate La-coated filters' sustained efficiency and stability, highlighting their potential for prolonged water purification applications.

Incorporation of MCN into CWFs has been demonstrated to significantly enhance the bactericidal efficiency.[52] The log removal values (LRVs) for *E. coli* show an escalating trend from 4.21 to 6.57 as the amount of MCN coating increases from 0 to 100 mg. This enhancement can be attributed to the increased generation of reactive species that play a crucial role in bacterial inactivation. The presence of MCN, particularly in conjunction with optimal light conditions, has been identified as a critical factor in augmenting the LRV. However, beyond the 100 mg threshold, the LRV reaches a plateau, indicating that there is an upper limit to the effective surface area of MCN@CWF. Simultaneously, the water flux experiences a decline from 129 to 109 mL/h with the increasing amount of MCN from 0 to 300 mg. This decline is likely due to the blockage of filter pores caused by the excessive coating of MCN.

The investigation of various techniques for integrating additives into CWFs represents a significant progression in enhancing their efficacy in purifying water. Approaches such as wet impregnation, drop-casting, in situ synthesis, blending, and painting have displayed distinct advantages in enhancing CWFs with substances such as lanthanum, silver nanoparticles, MCN, and nano-CeO_2. These additives enhance the antibacterial properties and impact the flow rate and efficiency of contaminant removal. Nanomaterials like nano ZnO and nano-CeO_2 are particularly noteworthy for their photocatalytic antibacterial activity and improved efficiency in removing arsenic, although they require a balance between efficiency and flow rate. The introduction of hydroxyapatite and iron oxide-biochar composite significantly affects the operational effectiveness of CWFs in eliminating fluoride and bacteria, showcasing technological advancements in water treatment. The long-term filtration experiments conducted with La-coated CWFs demonstrate sustained efficiency and stability, which are vital for extended applications in water purification. This comprehensive approach to enhancing water filtration presents new opportunities for future innovations in water treatment technologies, focusing on efficiency, sustainability, and adaptability to diverse environmental conditions.

3. LOW-COST CWFS

One important consideration in the implementation of CWF, especially in remote, rural, or developing areas, is cost-effectiveness. The fabrication cost of ceramic water filters varies, depending on the materials used and the specific

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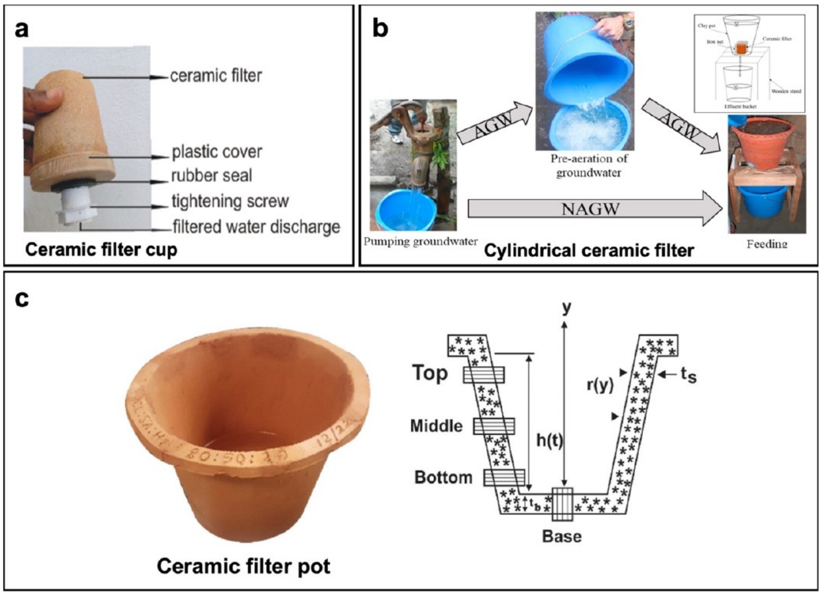

Figure 5. CWFs in simple geometries or shapes. (a) Filter cup. Reprinted with permission from ref 69. Copyright 2020, Springer Nature. (b) Cylindrical filter. Reprinted with permission from ref 70. Copyright 2021, Elsevier. (c) Filter pot. Reprinted from ref 43. Copyright 2022, The Authors. Under a Creative Commons CC BY license.

manufacturing process. As discussed in the previous section, CWFs can be produced using relatively simple methods and low-cost, locally available materials (Table 2). These materials include clay and combustible materials, such as rice husk, sawdust, leaves, and used papers. For example, ceramic filter has been fabricated from clay and nutshell powder, which are low-cost materials.[62] Asante-Kyei et al. used Akutuase clay, sawdust, and rice husks as local materials for filter production.[63] Another study by Rashad et al. utilized low-cost materials such as Aswan ball clay, Aswan kaolin, and a mixture of clay, potash feldspar, and quartz.[64] These studies demonstrate the potential for producing ceramic filters at a lower cost by utilizing waste resources and locally available materials.

CWFs can be fabricated using simple techniques, such as slip-casting and pressing, which do not require complex equipment. The design of the CWF is also simple and easy to fabricate. It can be molded into pot shapes, facilitating easy filtration operations (Figure 5). Alternatively, CWFs can be shaped into disc filters with a tube-like unit filter design, which are also easy to manufacture. CWFs also exhibited low operational and maintenance requirement.[65] These features make the CWF well-suited for decentralized water treatment, eliminating the need for specialized operators.

Another notable advantage of CWFs, contributing to their affordability, is its lower energy requirement. CWFs operate under low pressure, enabling them to function without the need for a pump (Figure 5). This low-pressure operation is possible due to the relatively large pore size and permeability of the filter (e.g., flux 289 L m^{-2} h^{-1} at 13.8 kPa[46]). This electricity-free operation is particularly crucial for remote and underserved areas with a limited energy and electricity infrastructure. Consequently, users do not incur additional energy costs while utilizing CWFs.

The life cycle analysis (LCA) of CWFs encompasses an in-depth evaluation of their environmental and economic impacts, highlighted by several studies. Ye et al.'s research on ceramic tile production reveals key environmental impacts such as marine ecotoxicity and climate change, quantifying the overall economic cost at \$2.77/m^2.[66] This study underscores the substantial contribution of inorganic chemicals to both environmental (12.9%) and economic (39.6%) burdens and suggests that adopting alternative electricity sources could significantly reduce impacts on climate change and marine ecotoxicity by 98.4% and 96.4%, respectively.[66] The analysis of the nano-CeO_2-modified ceramic filter water purifier (CeO_2−CFP) provides crucial insights into its environmental sustainability and water footprint, particularly in developing regions.[67] This study highlights the CeO_2−CFP's advanced manufacturing process' environmental efficiency and cost-effectiveness, emphasizing the importance of innovative production techniques. It identifies major contributors to the water footprint, including raw material and staff consumption, and proposes sustainable practices and improvements. Additionally, the study offers a strategic plan for mitigating the water footprint, focusing on elements such as the virtual water footprint (VWF) of rice husk and the number of CeO_2−CFP units produced daily.[67] Another study on ceramic sanitaryware production explores three scenarios using LCA.[68] The first scenario reveals significant environmental impacts from current production processes, particularly in terms of energy and material usage. The second scenario, involving wastewater recovery and new-generation ovens, shows a reduction in environmental impacts, particularly in abiotic depletion and ecotoxicity, but notes increased electricity consumption and emissions in waste recovery processes. The third scenario, incorporating a photovoltaic system and energy recovery, predicts further reductions in environmental impacts across most categories, highlighting the potential for substantial environmental benefits through these improvements. However, these enhancements may incur increased costs and maintenance complexities.[68]

Despite being constructed from relatively inexpensive materials, CWFs exhibit excellent performance in removing contaminants from water, making them suitable for household water supplies. While they may have limitations in eliminating

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Table 4. . Performances of CWFs

filter material	flow rate (L/h)	removal efficiency (% *E. coli*)	removal efficiency (% turbidity)	removal efficiency (% TDS)	ref
disk-shaped ceramic water filter made with kaolin and bentonite clays	73–108.2	100	80–90	50–70	75
ceramic filter made with Igbara odo clay and sawdust	1.9	100	80		73
biscuit ceramic filter (BCF) made with clay and sawdust	51	100	67	45.8	74
ceramic water filter with macadamia nutshell porogen	289		95–98	40	76
ceramic pot water filter (CPWF) made with clay and organic additives	39	100	96.5	75	77
ceramic filter made with clay and sawdust	1.2–2.0	99.99			38

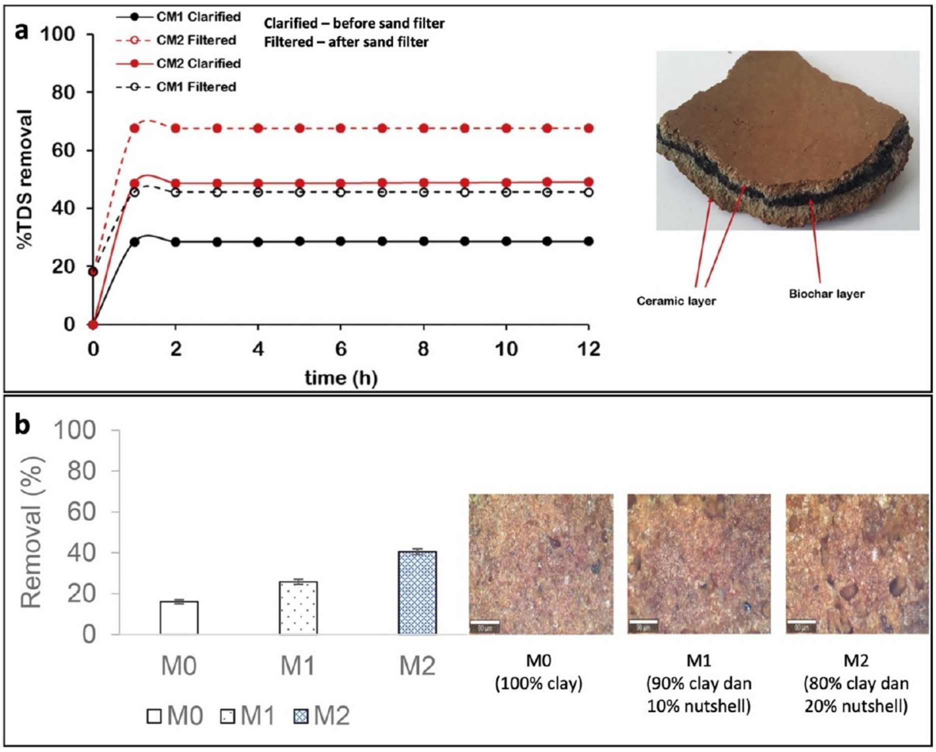

Figure 6. Performance of CWFs in (a) TDS (reproduced with permission from ref 74, copyright 2020, Elsevier) and (b) dye removal (reproduced with permission from ref 76, copyright 2023, Elsevier).

pathogens, this can be addressed by incorporating additives. Additionally, certain CWF variants without additives can achieve a high removal rate for bacteria (LRV of *E. coli* >6 in ref 44). For example, a CWF incorporating bone particles as an inexpensive additive can achieve an LRV of 4.89 for *E. coli* and LRV of 3.28 for fluoride.[53]

4. SEPARATION AND ANTIBACTERIAL PROPERTIES

4.1. Properties and Separation Performance of CWFs.

Ceramic pot filters (CPFs) derived from mixtures of clay, diatomite, and sawdust were subjected to analysis to evaluate their effectiveness in enhancing the accessibility of potable water in rural regions.[71] Extensive physical and chemical characterizations were conducted on these CPFs, which exhibited varying compositions, with Sample A (65% sawdust, 25% clay, and 10% diatomite) demonstrating the most favorable attributes. Following the firing process at temperatures of 850 and 950 °C, Sample A exhibited an optimal flow rate of 2.5 L/h, surpassing the performance of other samples, while also exhibiting reduced water absorption from 77% to 66% and apparent porosity from 67% to 59% as the temperature increased (Table 4). Chemical analyses confirmed the absence of harmful elements and the dominance of kaolinite clay in the CPFs. In terms of functionality, Sample A excelled in the removal of turbidity (93%), total dissolved solids (64%), total suspended solids (62%), and *E. coli* and coliform bacteria (100% each), thereby conforming to the standards set by the WHO for safe drinking water.

An analysis was conducted on CWFs to evaluate their efficacy in delivering potable water, unveiling significant disparities in their performance under laboratory and field conditions.[72] The CWFs, characterized by a pore fraction of 21.0–22.4% and an average maximum pore diameter ranging from 5.7 to 15.2 μm, were designed to eliminate bacteria predominantly through size exclusion. Laboratory experiments indicated a remarkably high average *E. coli* removal efficiency of 97.7–99.9%, indicating their potential effectiveness. Nevertheless, field studies conducted in Longhai City, China, exhibited a broader spectrum of removal efficiency, ranging from 75 to 100%, with an average of 94.7%. This discrepancy can be attributed to factors such as contamination of the filter element and receptacle during field use, underscoring the necessity for effective technology transfer and enhanced CWF design to bolster real-world performance. The study under-

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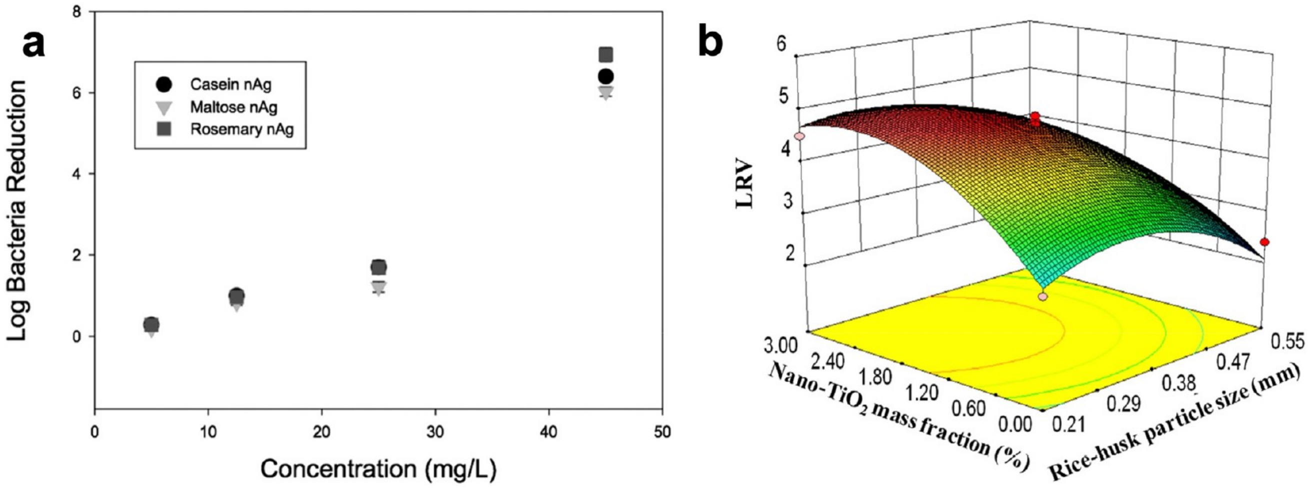

Figure 7. Bacterial removal by CWFs. (a) CWFs with nanosilver. Reproduced with permission from ref 82. Copyright 2017, Royal Society of Chemistry. (b) CWFs with nano-TiO_2. Reproduced with permission from ref 83. Copyright 2018, Elsevier.

scores the significance of addressing practical challenges encountered in the field to attain the same level of bacterial removal efficiency demonstrated in controlled laboratory settings, thereby guaranteeing the dependability and efficacy of CWFs in diverse and dynamic real-world environments.

In an investigation reported by Ajibade et al.,[73] a cost-efficient ceramic filter was developed to eliminate bacteria in wastewater, utilizing materials sourced from the local region of Ekiti state, Nigeria. The primary focus of the study was to produce a filter by employing a combination of clay and sawdust, with the optimal proportion determined as 50% Igbara odo clay and 50% sawdust. This composition showcased the most effective performance, attaining a flow rate of 1.9 L/h and removal efficiencies of 80% for coliform bacteria and 100% for *E. coli* bacteria. The values of the Atterberg limits and the color of the Ekiti clay samples were recorded systematically, thereby providing a comprehensive comprehension of the physical properties of the clay utilized. The flow rates of the filters were measured meticulously, reflecting the decrease in the water column height over a specified period. The findings of the research brought to light that the ceramic filters, especially those fabricated with a 50−50 blend of Igbara odo clay and sawdust, manifested superior performance levels in terms of both the flow rate and bacterial elimination efficiency.

In a study reported by Chaukura et al.,[74] the ceramic filter known as the "biscuit" ceramic filter (BCF) (Figure 6a) was composed of clay and sawdust. The BCF demonstrated an initial flow rate of 51 mL/min. In contrast, the control filter (CF), which was solely made from clay, exhibited a flow rate of 34 mL/min. The BCF exhibited greater removal efficiencies for total hardness (TH) at 42.5%, total dissolved solids (TDS) at 45.8% (Figure 6a), and turbidity at 67% compared to CF's respective efficiencies of 14.8%, 17.6%, and 56%. The impact strength of CF was measured at 60.78 ± 8.86 kJ/m^2, which notably surpassed BCF's measurement of 46.74 ± 10.25 kJ/m^2. BCF's water absorption was found to be 18.6 ± 2.86%, which was more significant than CF's measurement of 10.4 ± 2.07%, primarily due to sawdust's higher water absorption capacity. Throughout the 12 h, the BCF consistently maintained the exact total dissolved solids (TDS) for the clarified and filtered water. The turbidity removal for the water samples passing through CF was significantly lower at 56.3 ± 0.01% compared to BCF's measurement of 66.9 ± 0.25%. In terms of dissolved organic carbon (DOC) concentration, the permeate from BCF exhibited a more significant decrease than CF's.

Annan et al. evaluated disk-shaped ceramic water filters that utilize kaolin and bentonite clays.[75] The study focused on the physical and chemical properties of these filters and their performance in water filtration. By incorporating sawdust pore formers with sizes of 150, 250, and 350 μm, it was observed that the flow rate and volume of water filtered could be optimized by adjusting the particle size of the sawdust. The combination of Saltpond kaolin and Abonko clay, with a plasticity index of 14.9, displayed a medium plasticity that was advantageous for the fabrication process. Notably, larger sawdust sizes increased water filtration volume, and the flow rate improved in consecutive runs, starting at 73 mL/h for Ahwiam River water and 108.2 mL/h for Ashiyie River water. The removal efficiencies of turbidity, total suspended solids (TSS), and total dissolved solids (TDS) indicated that the filters could serve as an effective partial treatment for water, meeting WHO standards in specific configurations. XRD analysis confirmed the presence of silicon dioxide and aluminum silicate hydroxide, with a higher concentration of quartz in Abonko clay.

Mahlangu et al.[76] conducted an optimization study on the fabrication process of CWFs. This was achieved by adjusting the compression pressure and macadamia nutshell content, which served as a porogen, resulting in improved flow rates and the efficient removal of pollutants. Through thorough chemical and physical characterization, the most effective filter exhibited a flux of 289 L/(m^2 h), effectively reducing 40% of methyl orange (Figure 6b), 95−98% of turbidity, 40% of chromium(III), and 71% of lead(II). These improvements in filtration performance can be attributed to increased porosity and enhanced hydrophilicity, which result from the presence of oxygen-rich functional groups. Microscopic examinations conducted after the sintering process revealed a color change from green to brown, indicating the oxidation of the clay materials. Additionally, an increase in filter defects related to the porogen was observed, which is crucial for capturing water pollutants.

Solomon et al. conducted an investigation in which they produced ceramic pot water filters (CPWFs) by utilizing clays procured from various regions in Ethiopia.[77] In order to enhance the porosity of these CPWFs, organic additives such

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as sawdust and eragrostis Teflon husks were incorporated. Through an optimized preparation procedure, these CPWFs exhibited a discharge rate that reached its maximum at 39 mL/h. These filters played a significant role in improving the quality of water by reducing turbidity from 13 NTU to an impressively low level of 0.45 NTU. Additionally, the filters successfully lowered total dissolved solids from 1245 mg/L to a range of 360−530 mg/L and fluoride concentration from 3.4 to 0.053 mg/L, thus meeting the WHO standards. Furthermore, these filters proved to be highly effective in eliminating microbial contaminants, as they could eradicate up to 100% of total and fecal coliform bacteria.

Omoniyi et al. synthesized ceramic filters by integrating a 50:50 volume mixture of clay and sieved sawdust.[38] Upon sintering, the filters exhibited a diverse range of mean pore diameters, ranging from 0.73 to 1.07 μm. The porosity of the sintered filters increased as the sintering temperatures rose, and this increase was found to be directly related to their performance metrics. The quantitative analysis yielded *E. coli* log removal values (LRVs) between 4.46 and 4.89, indicating high efficacy in removing bacteria. However, the flow rates initially ranged between 1.2 and 2.0 L/h but gradually decreased over time, suggesting a decline in performance likely caused by pore clogging.

Results from reported studies reveal that these filters, made from local materials, not only effectively remove pathogens and turbidity but also retain significant amounts of dissolved and suspended solids. The variation in pore sizes, influenced by sintering temperatures and materials such as sawdust and diatomite, directly affects the efficiency of pollutant removal and flow rate efficiency, showcasing a sophisticated balance between porosity and filtration accuracy. Despite differences in performance between laboratory and field conditions, these filters demonstrate remarkable potential in mitigating the health risks associated with nonpotable water.

4.2. Antibacterial Activities and Bacterial Removal. The ability of ceramic water filters to eliminate bacteria (for example, in Figure 7a,b) is associated with various mechanisms. For example, ceramic water filters coated with lanthanum are believed to employ multiple mechanisms to remove bacteria from water.[44] First, the lanthanum coating enhances the distribution of pore sizes, enabling effective physical filtration for bacteria eradication. Second, the lanthanum coating diminishes the repulsive energy barrier between the lanthanum layer and bacterial cells, thereby facilitating bacteria immobilization on the filter. Last, the lanthanum layer binds bacteria by leveraging the bond between the lanthanum and phosphate groups on bacterial cells.

A ceramic water filter modified with Ag nanoparticles also demonstrates excellent antibacterial properties. The experimental results indicate that the ceramic water filter with Ag nanoparticles can increase the bacteria removal from 99% (without Ag nanoparticles) to 100%.[49] The mechanism of bacterial elimination may be related to the synergistic effect between filtration and disinfection with AgNPs.[49] By incorporating Ag/ZnO into the ceramic filter, the nanocomposite coating of Ag/ZnO plays a crucial role in eliminating *E. coli* from water using a combination of adsorption, photocatalysis, and ion release.[55] This leads to a remarkably efficient and effective removal of *E. coli* from the water, ensuring its safety for household purposes.[55] The silver-impregnated CWF also demonstrated effective *V. cholerae* removal. The silver-impregnated CWF achieves an impressive LRV of 5.6 against *V. cholerae*.[78]

Despite the excellent antibacterial properties of silver, its high cost poses a challenge for CWF. In order to address this issue, silver (Ag) is often combined with other antibacterial materials, such as zinc (Zn), to reduce the filter production costs. Zn serves as a complementary element to silver impregnation in CWF. Research has shown that when combined with Ag, higher concentrations of Zn lead to improved disinfection outcomes and effectively prevent bacterial growth.[60] Moreover, introducing Zn in CWF, particularly in clay compositions lacking natural Zn content, presents a significant opportunity to reduce cost without compromising the filters' bactericidal effectiveness. One of the other challenges in using silver as an additive is silver elution. Silver leaching from ceramic matrices has been recorded, as demonstrated in ref 79. Silver elution from these filters is impacted by various factors, including the type of silver, the application method, and the incoming water's chemical composition.[79] The separation of silver from ceramic filters is predominantly regulated by the dissolution of silver ions (Ag^+) and subsequent reactions involving the exchange of cations.[80]

Zhou et al. have developed a new ceramic filter that effectively kills bacteria in the dark and under visible light irradiation.[81] The filter membrane was made of TiO_2 nanobelts, which were loaded with Cu nanoparticles. The TiO_2 nanobelts provided more deposition sites for the Cu nanoparticles, and the Cu nanoparticles acted as a binder to help sinter the TiO_2 nanobelts into a strong and durable filter. The Cu nanoparticles also have an antibacterial effect of their own, and under visible light irradiation, they generate high-energy electron−hole pairs that further enhance the antibacterial effect.

Li et al. developed a ceramic disk filter coated with modified g-C_3N_4 (MCN@CDF).[52] MCN exhibits distinct antibacterial activity.[52] It possesses a high photocatalytic antibacterial activity, enabling it to eliminate bacteria in water through multiple mechanisms. When exposed to UV light, MCN can generate reactive oxygen species such as hydroxyl radicals and superoxide, effectively killing bacteria.[52] MCN can also produce electrons and holes that react with water to generate hydroxyl radicals, further contributing to the antibacterial effect.[52] Filters with MCN demonstrate an enhanced physical trapping capacity for bacteria, aiding in removing bacteria from water.[52]

4.3. Virus Removal. One of the drawbacks of ceramic water filters is their limited effectiveness in removing viruses. Specific antiviral agents can be incorporated into ceramic water filters to address this issue. Lanthanum (La) is an example of such an agent.[84] A CWF embedded with La was evaluated for its efficacy in filtering water contaminated with MS2, serving as a representative model virus for the study.[84] The findings revealed that CWFs, with a La coating, successfully treated 10000 pore volumes of virus-contaminated water.[84] This resulted in a viral removal rate exceeding the 5 LRV without detecting any infectious viruses in the filtered water.[84] This improved viral removal can be attributed to several factors, including enhanced attachment of virions to the filter surface due to the reduction of repulsive energy barriers, the presence of a secondary energy minimum, and the antiviral properties of the La-coated ceramic material.[84]

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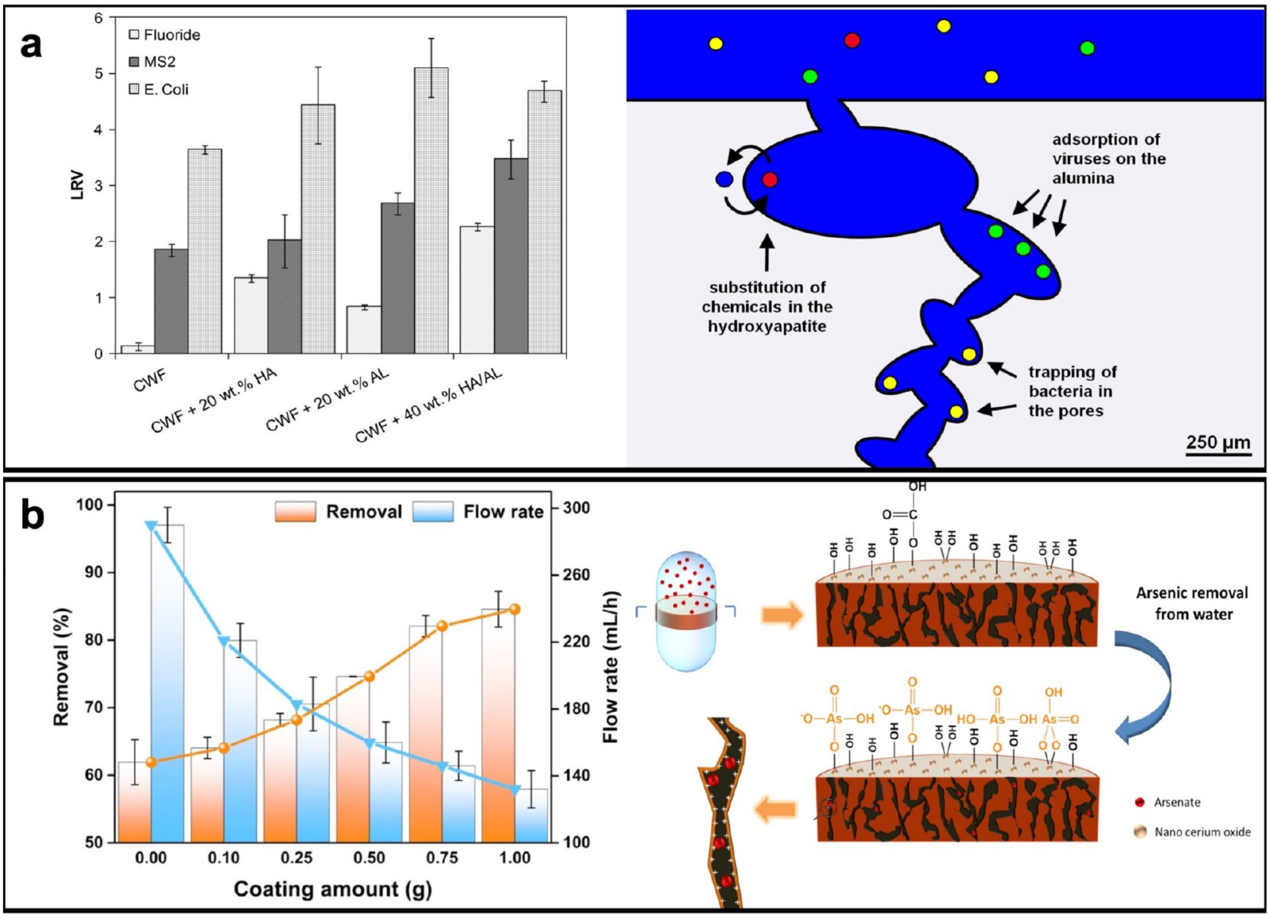

Figure 8. Contaminant removal and mechanism by CWF/additive. (a) Contaminant, bacteria, and virus removal with CWF/hydroxyapatite/alumina. Reproduced with permission from ref 16. Copyright 2019, American Society of Civil Engineers. (b) Arsenic removal with CWF/nano-CeO_2. Reproduced with permission from ref 56. Copyright 2021, Elsevier.

Adding silver and copper to a CWF also demonstrates the ability to inactivate MS2 Bacteriophage and Adenovirus.[85] The removal of MS2 phage by ceramic water filters is moderate, with approximately 71.95% and 75.98% removal rates achieved by filters embedded with silver and copper, respectively.[85] Analysis using transmission electron microscopy (TEM) indicates that the mechanism behind adenovirus inactivation by silver and copper may be associated with the impairment or elimination of viral fibers.[85]

CWF incorporating hydroxyapatite and alumina also demonstrated a high viral removal efficiency. CWF with hydroxyapatite and alumina is capable of removing the MS2 virus with an LRV value of 2.26.[16] This is believed to be due to the conservation of alumina, which leads to a substantial increase in the specific surface area. As a result, viral contaminants can be effectively adsorbed onto the surface of the filters, particularly within the alumina nanopores (Figure 8a).

4.4. Contaminant Removal. In addition to focusing on bacteria removal, several filters were also tested for their ability to eliminate dyes such as methyl orange and metals like chromium(III) and lead(II).[46] A study revealed that ceramic filters exhibited a remarkable 41% removal rate for methyl orange.[46] Moreover, the filter demonstrated a high removal efficiency of 99.9% for both lead and chromium.[46] This improvement in dye removal can be attributed to the observed increase in water flux with a higher combustible material content.[46] The pore size of the filter also influenced the removal of dye pollutants. Filters with larger pores allowed the passage of pollutants, resulting in lower removal rates.[46] Therefore, optimizing the filter's pore size and water flux is essential to balance effective pollutant removal and maintaining acceptable flow rates. The hydrophilic characteristics of the filters are responsible for the observed efficiency in removing pollutants. This can be attributed to the formation of a hydration layer on the surface of the filters. This hydration layer effectively reduces the interactions between the filters and pollutants, thus facilitating their removal. Additionally, the presence of oxygen-rich functional groups in the filters contributes to the adsorption of pollutants from the water. Furthermore, the heterogeneous surface morphologies of the filters greatly enhance their suitability for removing pollutants.

Ceramic filters composed of kaolin and zeolite have demonstrated impressive performance in eliminating textile dye, achieving a removal rate of up to 75%.[27] The excellent removal of textile dye is facilitated by the adsorption capabilities of zeolite, which is attributed to its negatively charged lattice structure that interacts with positively charged components of textile dye.

The incorporation of additives like Ca/Mg-phosphate into CWFs can enhance the removal of fluoride (defluoridation).[50] Chemisorption is the primary mechanism in removing fluoride from water using a modified Ca/Mg-phosphate CWF.[50] Chemisorption is a process in which fluoride ions (adsorbate)

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Figure 9. Simple decentralized water treatment using CWF. (a) CWF used in rural Tanzania. Reproduced with permission from ref 93. Copyright 2022, Elsevier. (b) CWFs tested in Nigeria. Reproduced from ref 90. Copyright 2021. IWA Publishing.

and a ceramic filter (adsorbent) exchange or share electrons to form chemical bonds. The calcium and magnesium cations in the filter establish bonds with fluoride ions, effectively eliminating them from the water. Although physisorption (physical adsorption) and precipitation may also contribute to some extent to fluoride uptake, chemisorption is the predominant mechanism.[50] Another additive material that helps enhance CWF's ability to remove fluoride is hydroxyapatite and bone particles. Both are capable of effectively removing fluoride through the mechanism of adsorption. The adsorption capacities for fluoride are 14.2 and 20.4 mg/L for CWF with hydroxyapatite and CWF with bone particles, respectively.[53] Iron oxide-biochar composite additives have also been tested to enhance CWF defluoridation capability.[58] CWF incorporating iron oxide-biochar employ electrostatic attraction and ion exchange processes as part of their defluoridation mechanism. The positively charged surface of the filter plays a vital role in attracting fluoride ions that carry a negative charge.

Arsenic is a contaminant that is often targeted for filtration using CWF. However, CWF alone may not effectively eliminate arsenic. One additive that proves beneficial in enhancing arsenic removal is nano-CeO_2.[56] When incorporated into CWF, nano-CeO_2 significantly improved arsenic removal by up to 85%.[56] The mechanism behind the removal of As(V) by CF-CeO_2 primarily involves ion exchange and electrostatic attraction (Figure 8b).

A study reported that preaeration using air can enhance the removal of contaminants, such as Fe and As, by CWF.[70] The preaeration process improves the removal of contaminants in household-based ceramic filters by facilitating the rapid oxidation of native Fe^{2+}. This process significantly increases the pH, oxidation−reduction potential, and dissolved oxygen levels in the groundwater, creating favorable conditions for the rapid chemical oxidation of Fe^{2+} and the formation of in situ hydrous ferric oxide flocs. X-ray absorption fine structure analysis suggested that As(III) is oxidized to As(V) during the Fe^{2+} oxidation process. The two-step oxidation in the preaerated groundwater system enhances the removal of As and Fe to 82−82% and 99%, respectively, compared to only 72% and 87%, respectively, in the nonaerated groundwater system. The preaeration step also significantly enhances the removal of Ca, Mn, and PO_4-P.[70]

5. CWF APPLICATIONS IN DECENTRALIZED WATER TREATMENT

Figure 9 illustrates examples of simple decentralized water treatment systems utilizing CWFs, as observed in rural communities across Tanzania, Ecuador, and Nigeria. CWF has been implemented in rural areas of Ecuador to improve

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drinking water quality.[86] The study evaluated the performance of Black CWF (BCWF) and its implementation in rural regions of Ecuador. BCWF fired in a reducing atmosphere represents a straightforward alteration to the traditional CWF, maintaining the affordability of the end product while enhancing viral elimination effectiveness by up to 3 log levels. The study included microbiological performance testing of BCWF in a laboratory, using water contaminated with *E. coli* and MS2 viruses, as well as testing physicochemical pollutant removal. Results indicate a low quality of drinking water in the studied communities. The use of water filters at the household level was reported to be low. The laboratory trials of BCWF demonstrated a reduction of bacteria by 5.36 logarithmic units and a reduction of viruses by 3.83 logarithmic units after 600 L of usage. The implementation of BCWF in the Santa Marianita community showed promising results in improving household drinking water quality using BCWF. However, it is important to strengthen the proper maintenance of BCWF for better field performance. The performance of BCWF applied in the low-income Ecuadorian highlands was also examined.[87] The results highlighted the effectiveness of BCWF in removing the bacteria. The BCWF could completely remove bacteria from the water, including antibiotic-resistant contaminants.

A study has been conducted to assess the performance of CWF in Longhai City, China, and to compare it with laboratory conditions.[88] During the field trials, the CWFs showed an average *E. coli* removal efficiency of 94.7% (75–100%). In contrast, laboratory studies demonstrated an average removal efficiency of 99.5% (97.7–99.9%). The variations in removal efficiency were attributed to contamination of the filter element and receptacle by end users during field use and cleaning. Effective technology transfer is necessary to minimize contamination and enhance performance under real conditions. Results of the study also suggest improvements in CWF design, such as lighter and less cumbersome filter elements, to reduce contamination during field use.

The application of CWF in treating water for 42 households in a remote mountainous area of Western Nepal has been evaluated and reported in ref 89. The effectiveness of filter handling on performance was assessed through microbiological analysis, interviews, and observations. The results showed that water quality decreased significantly when the source water was transferred to transport containers. The use of CWFs improved drinking water quality for around 40% of households. However, inadequate filter cleaning practices, such as using contaminated water, hands, and cleaning tools, resulted in filter contamination. Even disinfected filters had low removal efficiency for *E. coli* in the field trial compared to laboratory tests. Similar to the previous study, comprehensive training on proper filter handling and the development of better filter products is needed to improve their impact.

UNICEF has conducted operational research to evaluate the potential of CWF and biosand water filters for household point-of-use water treatment options in rural area of Nigeria.[90] In the rural area, only 3% of households have access to safe drinking water. By implementation of the research recommendations, CWF factories could enhance the bacterial removal efficiency of the filter, surpassing 97%. Results of the study showed that filter design and efficiency influence the filters' acceptability and the price users are willing to pay. However, the research also identified a low level of popularity for the filters, mainly due to inadequate promotion and marketing efforts.

A study has evaluated the efficiencies of various water filters available in the Tanzanian market.[91] Then, the results were used to select the best option for communities in rural areas of Tanzania. The evaluated filters include slow sand, bone char, biosand, membrane purifiers, and ceramic filters. The results indicate that ceramic filters are the most effective and affordable option. CWFs showed higher efficacy in removing pollutants, including turbidity, than other filters. Another advantage of ceramic filters is their low-cost material. CWFs can be prepared from locally available materials, such as rice husk, sawdust, clay, and flour, contributing to cost and accessibility.

Another study has evaluated the efficiency of CWFs in the Kambata Tabaro zone in southern Ethiopia.[92] The evaluated CWFs had average contaminant removal efficiencies of 46.23–88.98% for turbidity, total coliform, *E. coli*, calcium, magnesium, sulfate, phosphate, iron, and nitrite. Most CWFs effectively removed microbial contaminants from contaminated river water, surpassing the WHO standard.

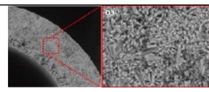
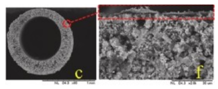
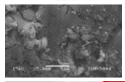
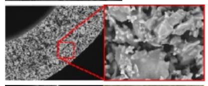
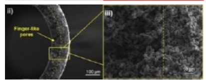
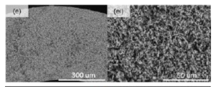
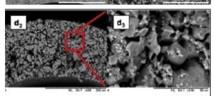
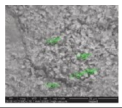
Results of the discussed studies provide valuable insights into the performance and potential of the application of CWFs in improving drinking water quality in various regions, especially in remote or rural areas. CWFs applied in those regions demonstrated promising results, significantly reducing water contaminants. However, proper maintenance and user training are crucial for optimal field performance.

6. CERAMIC MEMBRANES

Membranes are thin, selective barriers that separate two phases and allow the passage of certain substances while blocking others. The fundamental distinction between ceramic membranes and conventional CWFs is rooted in their disparate filtration mechanisms and scope of application.[94−96] Conventional CWFs engage in physical filtration, a process contingent upon the exclusion of larger particulate matter, predicated on the pore structure's ability to sieve particles at the particulate level. In juxtaposition, ceramic membranes operate through a sophisticated membrane filtration modality, proficient in the exclusion of finer particulate entities, as well as the sequestration of dissolved solids, bacteria, and viruses.[94−96] This advanced filtration is achieved through molecular sieving bolstered by surface chemical functionalities, facilitating interactions at the molecular scale, culminating in a more comprehensive purification paradigm.[94−96] Ceramic membranes offer superior filtration performance and improved separation efficiency and are used in industries with rigorous water quality standards.[97−99]

Ceramic membranes can be fabricated using various methods, including slip casting, tape casting, pressing, extrusion, and freeze casting.[95] Slip casting follows a procedure similar to that for conventional CWF preparation. Tape casting is a widely used technique for producing thin and smooth ceramic sheets, involving pouring a ceramic powder suspension into a reservoir and passing a ceramic tape under an adjustable casting knife.[100−102] Pressing is commonly employed in fundamental research for fabricating ceramic membranes, where a dry powder is pressed by using a machine and then heat-treated. In the extrusion method, a mixture of ceramic materials and additives is made pliable and forced through a shaped opening to determine the membrane's structure and properties.[103] After being dried, the membranes are heated at high temperatures to prevent cracking and achieve sintering. Freeze-casting, also known as ice-templating, is a method to

Table 5. . Ceramic Membranes Fabricated from Low-Cost Materials and Their Performances[a]

Low-cost materials	Method	Pore size	Performance	SEM	Ref.
Hydroxyapatite mode of cow bones	Extrusion	0.013 µm (smallest)	Color removal = 99.9%. COD removal = 80.1%. Turbidity removal = 99.4%. Conductivity removal = 30.1% Water flux = 88.3 L/m^{2}h (2 bar)		116
Guinea corn husk ash	Extrusion	0.11 – 0.18 µm	Microplastics removal = 88.8-97.2%. Water flux = 296.58 L/m^{2}h (2 bar)		117
Rice husk	Pressing	Unmeasured	Methylene blue removal = 99.6%		118
Waste rice husk	Extrusion	0.55–2.3 µm	Water flux = 303 L/m^{2}h (3 bar)		126
Palm oil fuel ash prepared from agricultural waste	Extrusion	20–50 µm	Maximum adsorption capacity of As(III) = 95.6 mg/g. Maximum adsorption capacity of As(V) = 98.3 mg/g. Water flux = 250.7 L/m^2.h		119
Natural occurring ball clay	Extrusion	0.61 µm	Water permeability = 1286 L/m^2 h bar		127
Clinoptilolite (natural zeolite)	Extrusion	-	Water flux = 228.257 L/m^2.h.bar. Ammonia removal = 96.67% Ammonia adsorption capacity = 12.47 mg/g		120
Aswan kaolin	Slip-casting	0.09–45 µm	Water flux = 22.9 L/m^2.h (atmospheric pressure). Bacterial removal = ~80%		121

[a]All figures in column 5 are reproduced with permissions from the references noted.

create highly porous ceramic membranes by freezing a ceramic slurry and allowing solvent crystals to grow, rejecting ceramic particles in the process.[104,105] A subsequent thermal treatment near the sintering temperature is necessary to improve the membrane mechanical properties.

Low-cost ceramic membranes have emerged as a promising alternative to expensive raw materials for membrane fabrication. By utilizing naturally available clays like kaolin clay, ball clay, and bentonite clay, as well as other earth minerals such as dolomite, natural pozzolan, and perlite, researchers have been able to synthesize ceramic membranes with thermal, chemical, and mechanical stabilities comparable to those of commercially available options but at a significantly reduced cost.[106] Industrial wastes like fly ash[107−109] and rice husk ash[110−112] have also been explored as alternative raw materials. These low-cost ceramic membranes find applications in various microfiltration processes, including treating oily wastewater and textile effluents and removing suspended matter from aqueous solutions.[113] Moreover, they can serve as coarse mechanical porous supports for ultra- and nanofiltration membranes.[114,115]

Table 5[126,127] summarizes various instances showcasing the performance of ceramic membranes manufactured by using inexpensive materials. One study successfully developed bioceramic hollow fiber membranes for treating industrial textile wastewater using hydroxyapatite derived from cow bones.[116] These membranes demonstrated exceptional qualities, particularly the membrane sintered at 1200 °C, which had a small pore size of 0.013 μm and a high mechanical strength of 202.5 MPa. They exhibited remarkable removal efficiencies for color, COD, turbidity, conductivity, and heavy metals while maintaining a stable flux of 88.3 L/m^2 h (at 2 bar) (see Table 5).

Another economical option was a silica-based ceramic hollow fiber microporous membrane made from guinea cornhusk ash, designed to remove microplastics from aqueous solutions.[117] This ceramic membrane proved effective in removing various types of microplastics, with a removal efficiency exceeding 88%, along with a relatively high water flux (>290 L/(m^2 h) at 2 bar).

In a different study, an adsorptive ceramic membrane was developed by using the dry pressing method. The membrane was composed of nanosilica obtained from low-cost rice husk, calcium phosphate, and ammonium acetate.[118] The study focused on the membrane's microstructure, its efficiency in removing dye (specifically methylene blue) from aqueous solutions, and its permeation flux. The silica membrane displayed remarkable adsorption capabilities for methylene blue, achieving a maximum removal rate of 99.6%. Furthermore, the membrane exhibited recyclability without significant performance degradation.

Ceramic membranes fabricated with modified palm oil fuel ash were also successful in efficiently removing arsenic, i.e. As(III) and As(V), from water.[119] These membranes exhibited outstanding arsenic removal rates (>95%) and adhered to the WHO standards for acceptable arsenic levels in water (10 μg/L). Preozonation of the ceramic membranes enhanced their adsorption capacity for arsenic, while postozonation effectively mitigated membrane fouling.

Additionally, hollow fiber ceramic membranes were developed using Clinoptilolite (natural zeolite).[120] These membranes were specifically designed for the efficient removal

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of ammonia from water and showcased impressive ammonia removal rates, achieving up to 96.67% efficiency along with a high permeability of 228.25 L/m^2 h bar.

Researchers have conducted tests on ceramic membranes constructed from inexpensive materials to evaluate their effectiveness in bacterial removal, and the results have shown high efficiency.[121] Ceramic membranes are highly effective in removing bacteria due to their smaller pore sizes compared to conventional filters. Additionally, incorporating antibacterial materials or other additives similar to those used in conventional CWF can further enhance the antibacterial properties of ceramic membranes. Another advantage of ceramic membranes is their ability to operate in crossflow mode,[122,123] which helps maintain long-term membrane productivity by decreasing foulant deposition.[124,125] Therefore, the membrane lifespan will also be prolonged. However, cross-flow operation is indeed slightly more complex and challenging to implement without a pump.

7. FUTURE OUTLOOKS AND DIRECTIONS

CWFs have emerged as a practical and cost-effective solution for providing clean water in underdeveloped regions, rural areas, and remote locations. CWFs have proven to be a valuable POU system due to its affordability, ease of operation, and efficient removal of contaminants and pathogens. While CWFs may have limitations in terms of productivity and the removal of viruses and chemical contaminants, ongoing research on nanofillers and antibacterial additives holds promise for enhancing its performance. However, further research is needed to identify relatively inexpensive additive materials with strong antibacterial properties to improve the performance of CWFs.

The preparation methods employed play a crucial role in determining the properties and performance of CWFs. Generally, CWFs are manufactured using slip-casting, extrusion or pressing, and hand-molding techniques, with slip-casting being the most commonly used method due to its simplicity and reproducibility. The choice of materials and their proper sieving and mixing are also critical factors. Fabrication conditions, such as the sintering temperature and compression pressure, significantly impact the properties of the CWF. Additives are often incorporated into the CWF matrix or applied to the surface to enhance its separation properties against water contaminants, bacteria, and viruses. Understanding and optimizing these preparation techniques as well as the function of additives are essential for developing CWF that is both effective and efficient in producing drinking water that meets the required standards.

Exploring 3D printing technology in the context of CWF fabrication opens up a new frontier in water treatment methodologies. Its rapid, on-site production and customization capacity presents a significant advancement in addressing varied and localized water contamination challenges. This technology's adaptability and speed are particularly crucial for quick responses to urgent contamination situations, thereby playing a vital role in safeguarding public health and ensuring the continuity of water supply in diverse environments. As such, 3D printing is a transformative and promising solution for pursuing effective and efficient water purification strategies.

The cost-effectiveness and affordability of CWFs make them a viable solution for decentralized drinking water systems. The simplicity of their production methods, utilizing locally available materials and straightforward fabrication techniques, contributes to their suitability for decentralized water treatment. The low operational and maintenance requirements as well as low energy consumption further enhance their practicality in areas with limited resources and infrastructure. While the incorporation of additives can address limitations in pathogen removal, certain CWFs without additives still demonstrate excellent performance in removing contaminants. CWFs prove to be an effective and economical option for the household water supply.

Studies evaluating the implementation of CWFs in different regions have shown promising results in improving drinking water quality, particularly in rural areas. The use of CWFs has led to significant reductions in water contaminants, including bacteria and viruses. However, proper maintenance and user training are vital to ensure optimal field performance. Therefore, long-term operation is necessary to determine the lifespan of a CWF and identify any challenges that may arise in its decentralized system operation.

Another type of ceramic filter is the ceramic membrane. Ceramic membranes offer excellent filtration performance and separation efficiency compared with conventional CWFs. They can be manufactured using affordable materials such as clays, earth minerals, and industrial waste. Numerous studies have demonstrated the impressive effectiveness of ceramic membranes made from low-cost materials in eliminating contaminants and meeting water quality standards. Furthermore, these membranes can operate in the cross-flow mode, ensuring sustained productivity by minimizing fouling. However, it should be noted that the cross-flow operation is slightly more complex and challenging to implement without the use of a pump. Reports on the application of ceramic membranes for decentralized systems are still limited.

It is apparent from the reported studies that CWFs have demonstrated potential as economically viable and practical solutions for providing clean water, particularly in underdeveloped and rural regions. Nevertheless, numerous opportunities exist for future research to further augment their efficacy. An extensive investigation is needed to identify cost-effective yet potent antibacterial additives that can enhance the CWF's ability to eliminate pathogens, with a specific emphasis on viruses and chemical contaminants. Subsequently, comprehending and optimizing the methods employed for CWF preparation, such as slip-casting, extrusion, pressing, and hand molding, assume the utmost significance in enhancing their performance. This entails exploring the novel technique of 3D printing, which offers swift and customizable solutions that can adapt to specific challenges posed by contamination and cater to urgent situations with prompt response times. The affordability and simplicity of CWFs, coupled with their minimal operational requirements, make them well-suited for decentralized drinking water systems. Nonetheless, studies about the long-term operational challenges, maintenance demands, and lifespan of CWFs within such systems are indispensable to ensuring their sustained efficacy. Furthermore, while ceramic membranes have demonstrated superior filtration efficiency and performance, ongoing research is still being conducted regarding their application in decentralized systems, especially in scenarios where cross-flow operation may prove challenging due to the absence of a pump. Addressing these research gaps can significantly contribute to developing more robust, efficient, and adaptable water purification systems that cater to diverse contexts and requirements.

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Notes

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