

Low-Cost Ceramic Filters and Biochar Filters as Point of Use Devices for Removal of Indicator Pathogens in Drinking Water: A Review

Desmond Dick Rutsito^{1*}, Masimba Katsande²

¹Chemistry Department, Bindura University of Science Education, Bindura, Zimbabwe

²Department of Chemical Engineering, National University of Science and Technology, Bulawayo, Zimbabwe

Email: *jaydenrutsito@gmail.com

How to cite this paper: Rutsito, D.D. and Katsande, M. (2025) Low-Cost Ceramic Filters and Biochar Filters as Point of Use Devices for Removal of Indicator Pathogens in Drinking Water: A Review. *Open Journal of Applied Sciences*, 15, 1095-1125.

<https://doi.org/10.4236/ojapps.2025.154077>

Received: March 4, 2025

Accepted: April 24, 2025

Published: April 27, 2025

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Abstract

In recent years, ceramic water filters and biochar filters have been used for the removal of organic, inorganic and to a lesser extent microbial contaminants in aqueous systems. Ceramic water filters and biochar filters have many benefits that include ease of operation, cheap and environmentally friendly, making them drinking water treatment technologies of choice especially in poor communities. The fabrication of ceramic water filters and the production of biochars are summarized in this review, along with the research status in the removal of indicator pathogens (primarily *Escherichia coli*) from drinking water using ceramic water filters and biochars. The mechanisms by which the microbes are removed by both technologies are explained, the advantages of using the techniques in water purification are examined, the future development prospects of using ceramic water filters and biochar, and the potential use of a hybrid biochar-ceramic water filter system in microbe remediation. From 2006 to 2022, research on the elimination of indicator pathogens was examined, with a focus on the application of different types of biochar (pristine or modified) and pot-shaped ceramic water filters. While the developing world has been slow to adopt low-cost filters for point-of-use water treatment in households against a backdrop of waterborne disease outbreaks in the poor countries due to lack of access to clean and safe water, the majority of research on both filters' ability to remove pathogens has been concentrated in the developed world.

Keywords

Indicator Pathogens, Point of Use, Ceramic, Biochar, Filters, Log Removal Value, Removal Efficiency

1. Introduction

Users of drinking water from a variety of unprotected sources may be exposed to potentially harmful inorganic and organic contaminants of anthropogenic or geogenic origins, as well as pathogenic or indicator organisms [1]. Potable water safety is a global issue [2]. Drinking tainted water is one of the greatest threats to human health; about 2.6 billion people lack access to clean drinking water and adequate sanitation [3]. According to [4], water is a key source of pathogens, including bacteria, viruses, and parasites. According to the World Health Organization [2], tainted water can spread more than 80 dangerous diseases. Economic progress and population well-being are ensured by having access to drinkable water and sanitary facilities and services. More than 2 million deaths among children under the age of five might be avoided each year with improved sanitation, water, and hygiene [5]. *Salmonella typhi* causes typhoid, *Vibrio cholerae* causes cholera, and *Escherichia coli* (*E. coli*) causes dysentery. These intestinal bacteria are responsible for the majority of current disease outbreaks. Poor hygiene and contaminated water sources are responsible for about 88% of diarrheal illnesses. Diarrheal diseases claim the lives of more than 1.3 million children worldwide each year [6]. According to [2], over 40% of people worldwide lack access to adequate sanitation and clean drinking water.

Worldwide, both industrialized and developing nations suffer from waterborne parasite protozoa infections, which cause endemic and epidemic human suffering [7]. In general, parasites are prevalent throughout the world and in all parts of nature [8]. Most endemic and epidemic diseases that affect people in poor nations are caused by them. Certain parasites can spread from animals to people, and their presence in food and water is extremely concerning for public health [9]. Because the danger of human infection was believed to be limited to particular geographic regions, host adaptations, intermediate hosts, and environmental conditions, food and waterborne parasites were not thoroughly examined in the past. However, this has changed as a result of food and water borne diseases outbreaks [10].

According to [5], parasites have been implicated in the deaths of children under the age of five. Infections with parasites affect one-third of the world's population. Up to 1.87 million children annually killed by foodborne and waterborne illnesses in developing nations. Water-borne illnesses are becoming more prevalent worldwide [4] [11] claim that parasite illnesses cause 1.76 billion instances of diarrhea and 842,000 fatalities annually.

The use of traditional water treatment methods, such as membrane filtration (reverse osmosis ultrafiltration), physicochemical treatment (coagulation, flocculation), and chemical treatment (ozonation, chlorination), is linked to a number of issues, including high operating costs and other difficulties that this review will briefly discuss [6]. Chemical or physical methods can be used to eliminate, deactivate, or destroy microorganisms in water. Filtration, adsorption, and distillation are examples of physical techniques. Chlorination, flocculation, ozonation or lime softening, photocatalysis, and electromagnetic radiation are examples of chemical

techniques [12].

Chlorination provides water with long-term protection by leaving behind chlorine that prevents germs and diseases from growing again. However, disinfection by products (DBPs), the most of which are carcinogenic, can be produced by ozonation and chlorination. There is a chance that germs will develop again when UV (ultra-violet) light is used [13]. Water can be effectively disinfected by membrane filtration, but membrane fouling necessitates expensive membrane replacement. Due to its cheap operating costs, high effectiveness, and ease of regeneration, the adsorption method of water treatment is still the preferred technology for microbial decontamination of drinking water [6]. In order to disinfect or remove indicator pathogens from drinking water, this article aims to increase interest in developing low-cost biochars and ceramic water filters. It also considers the possibility of using biochar filters in conjunction with ceramic water filters, first as point-of-use (POU) water treatment devices and then for large-scale drinking water treatment.

2. Objectives

- 1) To review the extent of global research on ceramic water filters and biochar filters in remediation of indicator pathogens in drinking water.
- 2) To review fabrication of ceramic water filters and biochar filters ideal for removal of indicator pathogens in drinking water.
- 3) To review applications of various types of ceramic water filters and biochar filters in removing indicator bacteria and viruses in drinking water.

3. Method

The two primary subjects examined in this study were found through searches on Google Scholar and Scopus: ceramic water filters for the removal of drinking water indicator pathogens and biochar filters for the removal of drinking water indicator pathogens or reference organisms (mostly *E. coli*). A total of 60 research publications on biochar filters and 35 on ceramic water filters were obtained as a result of the findings. Articles published after the specified period were not included in this assessment because the searches were carried out between August 2021 and December 2022. The relevance of the titles was examined in light of each category's exclusion criteria. The review only included the removal of bacteria and viruses using low-cost biochar and ceramic water filters. The review included papers published between the January 2006 to December 2022. Any paper written in other language other than English was excluded.

The research looked at the period 2006 to 2022 as a possible foundation of looking at the topic in question to also prove that further study is needed for the period from 2005 going back since no single study can be able to cover the period of more than 100 years. Just like any other studies conducted in English, there is no way the study could have looked at the studies conducted in all 7000 existing languages in the world. Thus, the study was limited to English, which has over the years been

considered a “universal language”.

4. Raw Materials for Making Ceramic Water Filters (CWF) Clay, Porogen, Firing of CWF

The foundation of ceramic water filters is clay, whose quality both dictates and affects the filter’s overall quality. Because of their porosity, kaolinite or terracotta clay are perfect for making ceramic filters. Low temperatures do not cause pores to form in the filters, although the hydraulic conductivity, porosity, and microbial removal efficiency of various clay sources vary. According to studies, a ceramic water filter that contains a lot of sand may have smaller pores, which could affect the filter’s flow rates and effectiveness in removing microorganisms. It was discovered that adding magnesium oxide to the filter improved its capacity to remove viruses [14]. Clayey materials, which are soil particles less than 2 µm in diameter, are used in the manufacture of CWF. A combination of clay, sand, silt, and amorphous material is known as clayey material. Water is added to the mixture of clayey material and porogen to create a paste, which is then compressed with a hydraulic press up to 1000 PSI to achieve the desired shape [14]-[16]. The material is crushed and sieved, and the burnout material, which is the porogen, is added, usually 5% - 45% by weight. The organic substance that creates pores and is utilized to make ceramic water filters is called a porogen. Burnout material is another name for this flammable organic substance. During the firing process, organic combustible materials such sawdust, rice husks, peanut husks, and coffee husks burn, causing pores to form in the filter [17].

After air drying, the molded filter is fired in a kiln at temperatures ranging from 350 to 1000 degrees Celsius. Microbes like *E. coli* and other pathogens can be filtered out of water by firing holes that have a diameter of 1 - 5 µm [18]. The porous structure acts as both flow channels for water passage and reaction sites for the elimination of contaminants such as bacteria, viruses, and other parasites. Porogen size and quantity have a significant impact on filter performance, according to study literature [17] [19].

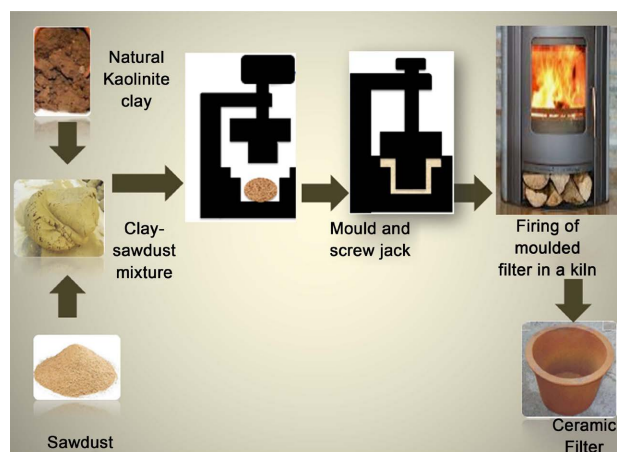


Figure 1. Schematic diagram for ceramic water filter manufacture.

When building filters, adding more porogen may result in higher flow rates. For instance, adding 2% - 31% rice husks boosted the filters' flow rate by 2 - 6 times [17]. Larger particle sizes in porogen material tend to create larger pores, which increases flow rates but may also reduce the effectiveness of microbial clearance [20]. In order to create a paste, clay and organic materials like rice husks, sawdust, and peanut shells are combined with water in the appropriate amounts. The paste is then compacted, shaped, and allowed to naturally dry [21]. The filter is fired once it has dried. Water smoking at 20°C - 120°C, decomposition at 120°C - 350°C, porogen combustion at 350°C - 450°C, transition to ceramic structure at 350°C - 700°C, carbon burns out at 700°C - 900°C, and vitrification at 950°C are the seven steps of the firing process, which takes place in a kiln. When the firing temperature was raised from 800°C to 950°C, a decrease in the removal of microbes was observed. This could have been caused by an increase in pore size brought on by the higher firing temperature [20]. More research is needed to determine the effects of firing temperatures and other atmospheric factors, especially when it comes to cleaning up microbiological pollutants in water. The steps involved in creating a ceramic water filter are summarized in the schematic diagram **Figure 1** above.

5. Silver Coating Ceramic Water Filters

Silver nanoparticles can be added to the filter after firing [22], silver is a biocide that can render bacteria and viruses inactive. Silver nanoparticles, an antibacterial ingredient, can be used on ceramic water filters to stop biofilm formation and post-treatment recontamination. Size exclusion, straining, and silver disinfection are the main methods used to remove bacteria from ceramic water filters coated with silver [19]. According to earlier studies, utilizing a silver-coated ceramic water filter resulted in a 99.999% bacterial removal rate, while using an uncoated ceramic water filter produced a 99.99% bacterial removal rate [20]. Several factors influence the use of silver-coated ceramic water filters to filter drinking water, including: 1) To guarantee long-lasting, effective disinfection, the dosage and quantity of silver administered should be carefully regulated. 2) Silver can be applied before or after the ceramic water filter is fired. When applied before firing, silver nanoparticles greatly increased retention and decreased release from ceramic water filters. This is in contrast to when silver is applied to the filter after firing. 3) The release of silver is significantly influenced by the chemistry of the water to be filtered, pH, ion valence, ionic strength, presence of chlorine, and natural organic matter. A key component of ceramic water filter efficacy is silver elution; the effluent's silver concentration should be maintained below the WHO's recommended limit of 0.1 mg/L. Interaction with bacteria that might get past the filter is started when silver ions and nanoparticles are released into the effluent [19]. Additionally, there are worries regarding the relatively short lifespan of ceramic water filters and the expensive costs of using silver nanoparticles, despite the fact that silver impregnation on ceramic water filters has demonstrated remarkable

potential in bacterial removal efficiency [23]. Two potential mechanisms are hypothesized to be involved in silver disinfection: 1) the formation of reaction oxygen species, and 2) the interaction between bacteria and silver.

According to [24], both processes have been shown to have harmful consequences and to limit bacterial DNA replication. In contrast to uncoated filters, which produced LRV of 4.6 and 5.5, filters coated by immersing in 600 mg/L colloidal silver managed LRV of 6 and 6.5. High Resolution Differential Interference Contrast Imaging revealed that silver successfully deactivated the oocysts in the batch treatment system in a study to remove *Cryptosporidium* from water. However, researchers were unable to determine whether the removal was due to silver disinfection or filtration by the ceramic matrix [25]. Biofilm accumulation on the filter's surface and bacterial growth within its body are both inhibited by silver.

Silver is absorbed into filter pores to function as a biocide when silver solution is applied to the inside and outside of the filter elements. The silver ions are then converted to elemental silver, which forms colloids inside the filter element [22]. For disinfection control, metal additions other than silver can be added to the ceramic water filter matrix. Zinc oxide, titanium oxide, and cupric oxide are among the ingredients. With the exception of titanium dioxide, which releases titanium ions upon photocatalysis, all metal species are believed to release ions into solution for disinfection. As ionic copper and a source of reaction for the production of oxygen species, cupric oxide has demonstrated good levels of microbial clearance and may help remove microorganisms. The recommended ingestion level for copper is 2 mg/L. Cupric oxide has demonstrated comparable and good potential in disinfecting bacteria contaminated water in cases better than silver nanoparticles [26]. This highlights an area of great opportunity for manufacturing adjustments.

The carbon-rich biomaterial known as biochar, which is depicted in **Figure 2** below, is created by pyrolyzing biomass at high temperatures with little to no oxygen present [1]. Low-cost biomaterials called biochars have a variety of uses, including carbon sequestration, soil conditioning, eliminating gaseous chemical pollutants from industrial flue gases, and eliminating both organic and inorganic contaminants from aqueous systems. According to [14] [20], biochars can be utilized in both their pristine and functionalized forms, which are produced by chemical, physical, and thermal activation processes and can be regenerated.

6. Biochar Resources

Low-cost biochars have been made from abundant, inexpensive biomass. Using both biological and thermal processes, biomass—such as wood chips, municipal sewage sludge, household bio-waste, straws, bagasse, and green waste—has been transformed into a variety of biochars [1] [27]-[29]. Many biomass forms, including animal dung, forestry residues, and agricultural crop wastes, have been proposed as feedstock for the production of biochar. Each biomass type's suitability as a feedstock is determined by a number of factors, including its physical composition



Figure 2. Low-cost feedstocks and corresponding biochars.

(density, moisture content, pH, ash content, cellulose/lignin ratio, volatiles, and calorific value), chemical constituents (fixed carbon, oxygen content, hydrogen content, and nitrogen content), and logistical, economic, and environmental factors [30] [31]. The chemical and physical characteristics of biochar, such as its pore size distribution, particle size distribution, and composition, are primarily determined by the feedstock composition. Additionally, the pyrolysis conditions, which include temperature, pressure, and residence firing time, influence the final biochar and its appropriateness for a given use [32].

A significant part of most feedstocks made from plants and crops is cellulose, a polymer of glucose that makes up 38% - 50% of the weight of lignocellulose biomass. Cellulose is the largest fraction of biomass. Because lignocellulosic biomass is so abundant globally, it might be used as a feedstock to generate biochar. Cellulose, hemicellulose, lignin, and trace amounts of extractive substances make up the majority of biomass [33], its average elemental composition is $\text{CH}_{1.4}\text{O}_{0.6}$. Globally, 7.5×10^{10} tons of cellulose are produced mostly through photosynthesis [27]. The second largest component of lignocellulosic biomass is hemicellulose, a polymer of xylose, which makes up 20% - 40% of the material by weight. Lignin makes up roughly 15% - 25% of the content of lignocellulosic biomass, making it the third biggest ingredient. It is a polymer of a 3-carbon chain attached to rings of 6 carbon atoms called phenyl-propane. In terms of structure softwood lignin polymer is different from hardwood [34].

7. Biochar Production Technologies

Biochar is made by thermochemically turning biomass into a solid product at temperatures above 300°C without oxygen; this process is known as pyrolysis, according to a review by [35]. Carbon, hydrogen, oxygen, nitrogen, and ash are all present in the solid result. The morphology of the source feedstock is reflected in the structure of biochar. Cross-linking, fragmentation, and breakdown of polymers at different temperatures are all part of the pyrolysis process. Non-condensable volatiles including carbon dioxide, carbon monoxide, hydrogen, nitrogen dioxide,

and hydrocarbons, as well as condensable tars such bio-oils and char—one of the products of interest in this review—are the main products of pyrolysis of biomass.

According to reports, woody biochar is gritty and contains up to 80% carbon. While biochar made from agricultural residues like manure, rye, or maize is finer and mechanically weaker, biochar made from biomass with a high lignin content, like olive husks, yields high yields of biochar with a high carbon content because lignin is stable to thermal degradation [35]. The amount of ash in biomass affects the amount of biochar that is produced. Prior studies have shown that when biomass is pyrolyzed, magnesium, sulphur, phosphorus, and calcium vaporize at very high temperatures while nitrogen, potassium, and chlorine vaporize at relatively low temperatures. A high output of biochar and high concentrations of magnesium, silica, chlorine, phosphorus, sulphur, and potassium are said to be produced by slow pyrolysis of biomass. While feedstocks like grain husks, grass, and straw have a high mineral content and yield large levels of biochar, woody biochar has a low ash content. The aforementioned feedstock with a high mineral concentration may contain up to 24% ash from rice husks, 41% ash from rice hulls, and up to 45% ash by weight from chicken litter [33]. Particle size reduced as the pyrolysis temperature was raised within the range of 450°C to 700°C, according to a study on the distribution of particle sizes on biochar made from wood chips and sawdust under various slow pyrolysis conditions

8. Combined Filter Technologies

[36] drew attention to the dramatic differences in the effectiveness of HWTS system II and HWTS System III performance within specific contexts due to the absence of relevant field-based studies that are key to understanding the performance of such technologies. This means that there must be consideration of contextual factors, as well as actual use patterns, during the application and assessment of HWTS systems in low resource environments. These findings also highlight the difficulty of achieving optimal microbial removal in HWTS systems for more difficult operational conditions.

[37] analyzed thoroughly the efficiency of laccase grafted membranes as innovative water filtration devices for the removal of endocrine-disrupting compounds (EDCs). This review points out the ineffectiveness of most conventional water treatment practices toward EDCs and offers alternative solutions through enzymatic membrane systems. Besides compiling the achievement in the review for this field, the authors also identify the gaps for the engineering application of laccase-based systems. The pointed needs are related to insufficient information on enzyme lifetime and membrane fouling, which the authors suggest is necessary to eliminate these obstacles.

[38] evaluated genotoxicity of combined filter backwash water (CFBW) that was reused directly into a drinking water treatment plant (WTP) by comet and micronucleus assays in zebrafish (*Danio rerio*). The research has shown that CFBW recycling did not significantly enhance the water sample genotoxicity in

comparison to CFBW processing in conventional ways. [39] offered a useful contribution as far as the economic analysis of low-pressure membrane filtration for potable water supply in the United Kingdom is concerned. It is worth noticing that they provide evidence not only for the capital investments, but also for the rest of the operating and maintenance expenses of the technology. The PV data, presented as cost curves for CAPEX, OPEX and total PV, illustrate the need to analyse the scale of the membrane installation, where smaller systems contribute to a more unfavorable OPEX-CAPEX ratio. As a whole, the reviewed range of literature provides a complex kaleidoscope of water filtration technologies.

[36] attested to the need of having field studies and local context when analyzing the effectiveness of HWTS systems, especially within these limited resource environments. [37] advocated for treatment methodologies using enzymatic membranes as a green alternative for the conventional water treatment technologies used for EDC removal, while [38] confirmed the possibility of CFBW recycling with no or very little augmentation in genotoxicity.

Also, [39] who performed cost analyses on low-pressure membrane filtration in the UK showed that scale is a fundamental factor for the cost effectiveness of such technologies and should be factored into their economic analysis. Their arguments underscore the importance of the current capital expenditure and shed some light on the subsequent operating and maintenance costs. With all these aspects combined, it seems there must be a more holistic framework that considers the local context, the comparative cost, and the effective sustainability for the advancement of appropriate water filtration technologies.

9. Thermal Conversion Processes

The three primary types of pyrolysis processes are slow, moderate, and rapid. Fast pyrolysis necessitates finely ground feedstock (less than 1 mm in particle size), high heating rates, high heat transfer rates, and quick cooling of the pyrolysis vapour, which usually produces tar or gas, in order to produce bio-crude products [34]. This review will solely discuss slow pyrolysis because it produces biochar using low-cost techniques.

10. Slow Pyrolysis

The process characteristics include a reactor operating at atmospheric pressure, a lengthy vapour residence time of roughly 10 seconds, a reactor temperature range of 450°C - 650°C, and extremely low heating rates of 0.01 - 2°Cs⁻¹. Increased cracking reactions made possible by these process conditions improve the yield of biochar while decreasing the formation of liquid organic matter. Condensation results from the process's slow pace, which promotes extensive secondary reactions within feedstock particles as well as in the gas and vapour phases [40]. Slow pyrolysis and intermediate pyrolysis are preferred for high charcoal outputs. According to earlier studies, the two methods are perfect for optimizing the production of biochar. The following pyrolysis conditions often favor high biochar yields:

1) low pyrolysis temperature < 400°C 2) high cellulose, nitrogen, lignin contents in the biomass 3) long vapour residence time 4) low heating rate 5) high pressure 6) large particle size of biomass 7) optimized heat integration 8) extended vapour solid contact [35].

11. Biochar Production Processes

There are two types of biochar production processes: batch and continuous. Brick and metal kilns, pits, and earth mounds are examples of batch operations. Although the technologies are straightforward and less expensive, they are unable to generate substantial feedstock burnoff and heat that cannot be recovered, as well as high yields of biochar [40]. Conversely, rotary kilns, drum-type pyrolysers, and screw-type pyrolysers are continuous process methods for producing biochar. Although the methods produce more biochar than batch methods, they are costly to purchase, maintain, and run, and they use a lot of energy [33]. But for the purposes of this analysis, the cost-effectiveness of the batch type processes was examined in more detail. Pit kilns and earth mounds have been in use since the early 20th century and are still common in the majority of developing nations. A hole is dug in the ground, filled with wood and other dry materials, with space at either end for air to enter and exit. The material is then lit at one end to create a pit or kiln. A thick layer of earth, about 20 cm deep enough to keep out air, is placed on top of the burning, less dense debris, including leaves and branches. Although it is constructed above ground, the earth mound kiln functions similarly to the pit kiln [41].

12. Applications of Ceramic Water Filters (CWF) and Biochar Filters in Removal of Pathogens in Drinking Water

Priority POU devices chosen for performance evaluation should, according to [2], 1) be suitable for low-income communities; 2) only purify enough water to serve a limited number of people in a day (household, clinics, schools); 3) be inexpensive; and 4) not require plumbing and should be free-standing. As indicated in **Table 1** and **Table 2** below, the WHO evaluation scheme for drinking water POU devices suggests testing water for three groups of pathogens (bacteria, viruses, and protozoa) for microbiological safety. Drinking water is dangerous for human consumption if it contains fecal coliforms and *E. coli* [42].

Table 1. Test organisms of WHO scheme and recommended microbiological performance criteria.

Recommended targets for microbiological reduction by POU water treatment systems				
Pathogen class	Organism	Key considerations in POU water technology evaluation	Very high pathogen removal	High pathogen removal
Bacteria	<i>E. coli</i>	Well defined faecal indicator organism frequently found in raw water sources. Most sensitive organism to disinfection	≥4	≥2

Continued

Virus	MS2 and PhiX174 human viral surrogates	Commonly used indicator for human viruses. Well characterized susceptibility to various disinfectants	≥5	≥3
Protozoa	<i>Cryptosporidium parvum</i> oocysts	Relatively resistant to chemical disinfectants but sensitive to ultra violet irradiation. Readily removable physically	≥4	≥2

1 log removal value = 90%, 2 LRV = 99%, 3 LRV = 99.9%, 4 LRV = 99.99 %, 5 LRV = 99.999%.

Table 2. Interpretation of filter performance based on pathogen removal efficiency.

Log removal values (LRVs)	Filter performance
1 - 2 LRVs	Fair pathogen removal
2 - 3 LRVs	Good pathogen removal
4 and above LRVs	Excellent pathogen removal

The filtration process' ability to remove microorganisms from water is dependent on a number of factors, including the organisms' size, density, and surface charge, as well as the filtering material and filtration rate [4]. Sedimentation is a difficult method of eliminating bacteria. Filtration can be used to get rid of protozoan parasites. Chemical treatment, sedimentation, settling, and filtering are techniques that have been employed to eliminate microorganisms from water [2]. The most often used disinfectant for treating drinking water is chlorine. It has been shown that point-of-use disinfection reduces newborn diarrhea cases caused by *Escherichia coli* (*E. coli*) by 29%. However, chlorine has drawbacks, such as a strong smell, a foul taste in water due to interactions with organic debris, and a tendency for some protozoa to become resistant [43].

Point of use (POU) devices are ideal for rural areas where communities are not served by centralized water distribution systems [3]. In rural areas, only 53 % of the population has access to potable water free from contamination. More efforts should be channeled towards provision of water treatment systems capable of removing pathogens in drinking water [2]. In the developing world namely sub-Saharan Africa, Oceania, Southern and Central Asia, water distribution and water purification technologies are unavailable or outdated due to social, political and economic factors [2]. An estimated 4 million people globally are using ceramic water filters to purify drinking water daily, therefore positively contributing to public health [19]. Low-cost ceramic filters have been successfully used to treat drinking water in 20 developing countries.

POU water purification technology that is easy to use, economical, socially and culturally acceptable, low maintenance, environmentally sustainable, requires no external energy source or consumable supplies, and is extremely cost-effective should be taken into consideration in the aforementioned areas [20]. By gravitationally filtering through porous ceramic media, ceramic water filters (CWFs)

composed of clay and porogens (sawdust, rice husks, crushed nut hulls, and egg shells) have been shown to efficiently eliminate bacteria. CWF has been formed into a variety of shapes, including disks, candles, tubes, and pots. Microorganisms have been eradicated with the use of silver coating [20]. According to reports, more than 100,000 households in Cambodia purify their drinking water using inexpensive ceramic water purifiers [44].

According to a ten-year study, an average family used 37960 liters of water, which was supplied by a centralized water treatment and distribution system or POU technology. In terms of lowering water-borne diarrheal diseases in children under five and the general population, ceramic filters were shown to be three to six times more effective than centralized water distribution systems. In four of the five assessed life cycle impacts—water use, energy use, particulate matter emissions, and pollution reduction—ceramic filters demonstrated superior environmental qualities. It has been demonstrated that POU technology is a more environmentally friendly option than centralized water treatment systems for treating drinking water in impoverished nations [45].

Waterborne bacterial and viral pathogens were eliminated using clay-based ceramic filters. According to research, 99.7% of *E. coli* and 9.4% of all coliforms have been eliminated from water, along with viruses, bacteria, and protozoan parasites) [46]. Over more than 600 liters of throughput, a mean of roughly 90% - 99% reduction for viruses and 99% reduction for *E. coli* was recorded. The cost to construct the filters was less than \$10 USD [44]. There have been reports of removal efficiency of 90% - 99.9% for bacteria and 99 percent for parasitic protozoa. According to [21], filter samples showed up to 75% reductions in microbial load. Clay and sawdust have been used in different quantities to create ceramic filters as follows; 40:60, 30:70 and 50:50.

The best-performing filter that effectively eliminated microorganisms from water was made with a 50:50 clay to sawdust ratio. The inexpensive ceramic filter achieved 100% removal efficiency for *E. coli* and 80% removal efficiency for coliforms. The filtration process had a flow rate of 1.9 L/h. However, it was found that the increase in the percentage of sawdust added should not be less than 30% and not exceed 70% in order to achieve a balance between filter porosity and mechanical strength [15]. Diarrhea and other waterborne illnesses were successfully decreased using ceramic water filtering. The temperature and flavor of filtered water are unaffected by ceramic water filtration. In poor nations, commercial ceramic water filters have gained popularity due to their long lifespan of up to 5 years effectively eliminating pathogens in water [20] [44] [47].

Ecuadorian-made ceramic water filters shown good results in lowering the microbial load in both simulated and real water samples. By constantly filtering water tainted with MS2 bacteriophages and *E. coli*, the study evaluated the microbial removal capabilities of black ceramic water filters. According to [48], the results of 600-liter black ceramic water filter testing revealed 3.83 logarithms for virus removal and 5.36 logarithms for bacterial removal. A ceramic water filter was cre-

ated that can eliminate *E. coli*, MS2 bacteriophages, and human adenoviruses. A reductive environment was used to burn the ceramic filter. The virus levels were brought down to WHO-permissible levels, and the filter's bacterial and viral removal efficiencies were higher than 2.5 log and 3 log, respectively.

The increased virus elimination was ascribed to the ceramic water filter's wide surface area and larger fraction of positive Z potential fraction [49]. The microbial reduction efficacy of a low-cost ceramic filter revealed 97.5% and 99.05% of total coliforms for well and lagoon water, respectively. In both instances, the microbial reduction efficiencies for fecal streptococci and *E. coli* were 100%. However, according to [50], the 2.5-liter flow rate in three hours is not economically viable. It was found that a pot-shaped ceramic filter had average removal rates of 87.6% for *E. coli* and 86.3% for total coliforms, with a flow rate of 226.66 mL/h. The number of microorganisms eliminated was in line with WHO guidelines. 80% of the filter was made of clay, 25% sawdust, 5% grog fired at 750°C - 800°C.

Out of all the filters examined, this one exhibited the best microbiological removal efficiency and the least porosity [51]. The microbial removal effectiveness in a related study that employed 15% sawdust together with the same amount of clay and grog to create the filter ranged from 80% to 97.5% [52].

Although ozonation and chlorination methods are good at reducing microbial pathogens, the production of harmful disinfection byproducts has forced researchers to look at other methods of disinfecting water. There have been reports of the use of silver coated ceramic water filters (CWF) as a point-of-use water treatment method in rural, peri-urban, and informal urban households to remove *E. coli*, an indication for pathogen in drinking water. The ceramic pot filter (CPF) in particular is part of the CWF. Two filters, one from Mukondeni and the other from Sese in Zimbabwe, were able to completely eliminate the number of colonies forming units in filtered water in one particular investigation. The raw water's microbiological quality was generally enhanced by the filters. However, compared to the Mukondeni filter, the Sese ceramic water filter had a slower filtration rate due to its lower percentage of organic flammable materials. The turbidity of the filtered water was reduced to less than 1 NTU by both filters [53]. However, the CWF's constant filtrations caused the pores that capture pathogens to get clogged, which made cleaning the CWF necessary to clear the obstructions [19]. An inexpensive CWF created by earlier researchers was able to LRV- $\log_{10} > 4$ with 99.99% reduction efficiency.

POU water treatment systems should generate drinking water that satisfies 6 \log_{10} reduction of bacteria, 4 \log_{10} reduction of viruses, and 3 \log_{10} reduction of protozoa, according to the National Sanitation Foundation and the United States Environmental Protection Agency (USEPA). However, the CPFs were not coated with silver for this investigation [54]. The ideal filter has a high flow rate and a high bacteria elimination effectiveness. Two important performance metrics for a ceramic water filter are flow rate and the effectiveness of microbiological elimination. In an effort to create a ceramic filter with the best possible performance—

high flow rate and microbial elimination efficiency—different firing temperatures, clay ratios, and porogen mixing ratios have been tried [20].

Literature claims that the most often used ceramic water filter based on performance is the pot-shaped kind. There have been reports of flow rates between two and three liters per hour, two log removal values (LRV) without silver coating, and four LRV with silver coating [55]. Research is still needed to build a filter that can remove microorganisms effectively while maintaining a high flow rate.

To determine the impact of sawdust content and AgNPs coating on the filtration and subsequent removal of *E. coli* in drinking water, tests were conducted on ceramic water filters manufactured in Guatemala. According to reports, filters with higher porosity were able to eliminate a larger percentage of *E. coli* than those with lower porosity. This was because proportion of combustible material present in highly porous filters, assuming that structural probity of filters is not compromised. Analysis of filtered water samples revealed that the average ionic silver content was 0.02 mg/L, compared to an acceptable standard of 0.1 mg/L, the turbidity was 0.18 NTU, and the bacterial removal was 92%. In general, the CWF has shown a satisfactory ability to enhance the drinking water's microbiological purity [56]. According to a study on the use of silver on CPFs, CPF impregnated with silver nitrate outperforms AgNPs-coated CPF in terms of eliminating microorganisms from drinking water. The clearance efficiency of the silver nitrate-coated CPF for *E. coli* and total coliforms were 95% and 99%, respectively. Silver concentrations released by the silver nitrate-coated and AgNP-coated CPFs on both sides of the filters were below the advised WHO levels for potable water limit of 100 ppm. Additionally, the use of silver nitrate ensures safety and lowers production costs by limiting the possibility that users or filter manufacturers will inhale the chemical [57].

For the purpose of eliminating *Salmonella*, *E. coli*, and other bacteria, researchers have compared the effectiveness of a ceramic silver impregnated pot filter (CSF) system that combines silver-coated activated granular carbon and zeolite CSF + GAC-Z with a traditional silver-coated ceramic water filter. For *Salmonella ssp.* and *E. coli*, the highest removal efficiencies were 99.98% for CSF and 99.98% for CSF + GAC-Z. The two systems' bacterial elimination efficiency did not differ statistically significantly; nevertheless, the combination of CSF with the adsorption technique was discovered to be socially effective and efficient. According to WHO guidelines, the filtered water was classified as low risk bacteriologically even though the bacterial removal effectiveness was less than 100% [58]. Contrary to what other studies have claimed, prior researchers have found that the bacterial removal efficiency of CWFs are mostly influenced by the influent water's contact time with silver during the filtration residence period rather than the amount of burnt material in the CWF. The bacterial elimination efficiency of CWF is not significantly affected by the various silver applications on the CPF, *i.e.*, no coating, only outside, and inside and outside. There were no discernible variations in log removal values (LRVs) between filters with various silver applications. The study found that the most crucial factor in ensuring that silver inactivated *E. coli* was

the water's residence time in the container. The results demonstrated that while CWF alone is effective at eliminating microorganisms, the addition of antimicrobial agents like AgNPs, copper, and iron composites is optimal. However, particular attention must be paid to the final product's overall cost, as it shouldn't be too high for underprivileged communities to afford [19]. CPFs composed of the following percentage ratios of clay, diatomite, and sawdust mixes, for example, A (50 sawdust, 25 clay, diatomite 10), B (60 sawdust, 25 clay, diatomite 15), and C (50 sawdust, 25 clay, diatomite 25) and D (sawdust 45, clay 25, diatomite 30) were used for removal of *E. coli* and coliforms in drinking water. Filters A and B had flow rates of 2.5 L/h and 2 L/h, respectively, and tests on the filtered water showed 100% removal efficiency for both *E. coli* and coliforms.

In a study conducted out to test effectiveness of ceramic filters in reducing diarrheal illnesses, whereby 61 rural households in Zimbabwe and South Africa were provided with CPFs to treat their home drinking water. There was a lower incidence of both bloody and non-bloody diarrhea among CPF users. In children in rural South Africa and Zimbabwe, the availability of CPFs was linked to an 80% reduction in the incidence of both bloody and non-bloody diarrhea. The *E. coli* levels were lower in the CPF-treated water. *Shigella* species, *Salmonella typhi*, *E. coli*, *Vibrio cholerae*, *Klebsiella*, and protozoan parasites including *Giardia* and *Cryptosporidium* have all been shown to be successfully eliminated by CPFs impregnated with AgNPs. When CPFs are used correctly, high-quality drinking water can be obtained; nevertheless, hand washing and other excellent hygiene habits also significantly reduce the occurrence of diarrhea [59]. POU filters manufactured in Nicaragua initially demonstrated disinfection efficiencies between 3 and 4.5 log₁₀; however, once *E. coli*-spiked water was loaded, the microbe disinfection efficiency decreased. Bacterial disinfection efficiency increased to 3.8 - 4.5 log₁₀ after some of the CPFs were recoated with colloidal silver. Colloidal silver is successful at reducing bacterial pollutants in water, according to the study; however, extended use of the filters reduced their efficacy, as seen by the release of germs into the filtered water [23]. Researchers have used chitosan, a potential natural coagulant, as a pretreatment step before CPF filtration in an effort to rid drinking water of indicator bacteria. The drinking water's turbidity, virus, and bacterial concentrations were all decreased by the integrated filtering system. With a dosage of 30 mg/L of chitosan acetate plus CPF, the maximum log₁₀ reduction of MS2 coliphage was 4.5. The researcher will not go into great depth on virus removal with CPF in this review because that is outside the scope of the study. With a chitosan lactate and CPF concentration of 30 mg/L, the maximum log₁₀ decrease of *E. coli* was 7.5. However, when locally available materials are employed, employing chitosan acetate in addition to CPFs is more costly than using CPF alone [25]. CWF doped with alumina and hydro apatite. During the fire process, the two additives were preserved, and the resulting nanopores raised the CWF's specific surface area from 3.7 to 21 m²·g⁻¹. When evaluated, the filters were able to remove bacterial and viral pollutants with efficiencies of 99.998% and

99.45%, respectively, and log reduction values (LRV) of 4.69 and 2.26. Viral and bacterial pollutants were eliminated from drinking water through adsorption on surfaces, substitution in hydroxyapatite, and pore-trapping [60].

As demonstrated above, CPFs have been widely employed to rid water of different microorganisms. However, using CPFs alone has some drawbacks, such as 1) the reintroduction of germs into filtered water after extended use. 2) After several filtration passes, the microorganisms finally adhere to the CPF's surface, resulting in the creation of a biofilm layer. 3) a comparatively shorter lifespan in terms of filtration efficiency required to generate drinkable water, and 4) the challenges of scaling up the use of CPF to large scale, such as when the technology is used to treat water for industrial or population consumption in a metropolitan area. Another inexpensive filter that has been extensively utilized for cleaning up various pollutants such as organic, inorganic and microbial contaminants in drinking water is biochar. Since this component of water purification has not received much attention, the researcher will concentrate on using biochar to remove bacterial microorganisms for the purposes of this review. The study will examine the removal of bacterial germs in drinking water using biochar filters, as reported by different studies, in addition to the removal of microorganisms in drinking water using CWF.

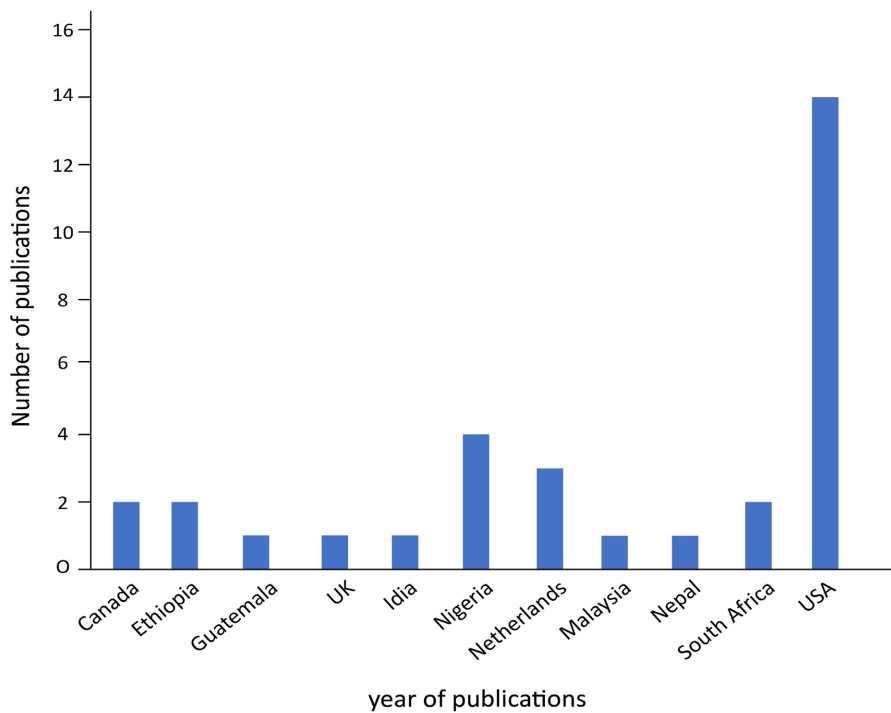


Figure 3. Number of research articles published on ceramic water filters for removal of microbial pathogens in water in different parts of the world between 2006 and 2022.

As evidenced by the largest number of papers in **Figure 3** throughout the review period (2006-2022), research on the removal of indicator pathogens using ceramic water filters has been conducted extensively in the USA. **Figure 4** illustrates that

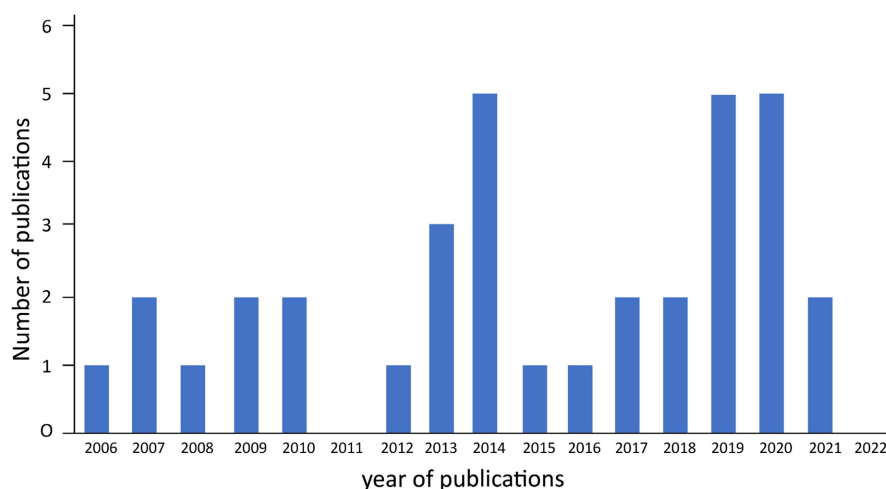


Figure 4. Number of research articles published between 2006 and 2022 on ceramic water filters for removal of microbial pathogens in water.

throughout the time under examination (2006-2022), the largest number of research articles published in a calendar year was five, which occurred in 2014, 2019, and 2020. There is very little study on ceramic water filters for pathogen elimination, and more research is required before disadvantaged populations may truly adopt POU water treatment methods. Only three African nations—Nigeria, South Africa, and Ethiopia—have made contributions to microbial remediation research.

Since the low-cost materials would benefit their home countries more in terms of access to clean drinking water and ecologically friendly water treatment processes, researchers in developing nations should focus more on POU technology. In contrast to poor countries, which primarily rely on donor funds and where a large portion of the population lacks access to properly treated, safe drinking water—which is typically distributed using centralized water treatment systems—developed countries have the financial means to purchase pricey water treatment technologies for their citizens.

Biochar-based pathogen and indicator organism remediation has been widely used to remediate urban stormwater runoff, which contains a wide range of pollutants and eventually enters surface water sources like lakes, dams, and streams.

Irrigation using such polluted water may result in microbial contamination of vegetables and eventually negatively impact health of end of chain consumers [61]. Stormwater and other bodies of water have been shown to contain fecal indicator bacteria such *Enterococci* and *E. coli*. The aforementioned fecal indicator microorganisms have been eliminated using biochar-based filters [62]. A study found that using bamboo biochar treated with zero-valent iron (ZVI) reduced the development of *E. coli* by nearly 50% when compared to a blank control culture that had a colony forming unit count of 4.1×10^{-8} CFU/ml. Subsequent research created a stabilized AgNPs-ZVI biochar nanocomposite by combining ZVI modified bamboo biochar with silver ions, which effectively stopped the growth of *E.*

coli cells [63] [64].

To disinfect drinking water, a chitosan corn straw biochar nano-silver composite (CTS-C-Ag) was made. The combination was applied to water containing 2.1×10^5 CFU/ml of *E. coli*. For drinking water filtration, the composite demonstrated good reusability and long-lasting, superior antibacterial action against *E. coli* [63]. To improve their ability to remove bacteria, sand biofilters were biochar modified with 5 weight percent biochar. The biochar-amended sand filters immobilized the bacteria during continuous, intermittent flow and retained up to three orders of magnitude more *E. coli*. High retention on the charcoal filter, which boosted *E. coli* adhesion, was credited with the high pathogen removal capacity [65].

The filtering capabilities of softwood biochar and sand filters were compared in a related study, which revealed that biochar was able to retain up to three orders of magnitude more *E. coli*. Although the removal effectiveness was still better than that of sand filters, the presence of natural organic materials reduced the biochar's ability to remove *E. coli*. According to the study, repulsive electrostatic interactions, van der Waals forces, and hydrophobic attraction were responsible for the elimination of *E. coli* [66]. One particularly noteworthy study found that the biochar from immaculate waste wood pellets decreased the amount of *E. coli* in urban storm water runoff from 7400 CFU/100ml to 500 MPN/100ml. They used a column filtration method. Size exclusion and surface attachment were linked to the elimination of larger pathogens like amoeba and protozoa, as well as the adsorption of negatively charged bacterial cells followed by their death off. Antimicrobials derived from biochar were one of the main mechanisms for pathogen removal. *E. coli* and Enterococci have been eliminated from storm water by earlier studies using hard and soft wood biochars. According to the study, *E. coli* was removed more successfully (99.29%) than Enterococci (98.18%). The ratio of sand to biochar (v/v) in the biofilters was 7:3. For both *E. coli* and Enterococci, potential removal methods included hydrophobic adhesion, electrostatic deposition, steric hindrance, or polymer bridging. Soft wood biochar was utilized in a related investigation to remediate *E. coli* and Enterococci; the starting bacterial counts were 85.114 MPN/ml and 19.498 MPN/ml, respectively. *E. coli* and Enterococci had clearance efficiency of 89.77 percent and 90.45 percent, respectively. Pathogen inactivation by turbidity reduction by the highly porous structure and enhanced adsorption due to the biochar's specific surface area were the proposed removal methods.

Saccharomyces cerevisiae was successfully extracted from diluted wastewater. The size of the biochar particles had a significant impact on the effectiveness of the microbial eradication. The majority of target pathogens were consistently eliminated at least $1 \log_{10}$ CFU at a minimum particle size of $d_{10} = 1.4$ mm.

In order to remove *E. coli* from drinking water, several researchers evaluated different modified biochars made from the same feedstock with pure forestry woody waste biochar. Assuming a starting concentration of $0.3 - 3.2 \times 10^6$ CFU/ml and an operating pH of 7.1 at room temperature, the pristine biochar's *E. coli*

removal efficiency was 96.60%, while the sulphuric acid modified biochar's was 96.70%. The phosphoric acid modified biochar also achieved a 96% removal efficiency. Biochar treated with potassium hydroxide and biochar modified with amino acids had removal efficiency of 96.4% and 92.1%, respectively, for *E. coli*. Pore straining, hydrophobic attractions, interaction potential because of attractive van der Waals, and repulsive electrostatic interactions were proposed as the removal processes in this work [67] [68].

With a low minimum inhibitory concentration of 1.26 µg/ml, potassium hydroxide silver-coated cocoa pod biochar demonstrated exceptional antibacterial activity against *Salmonella*, *P. aeruginosa*, and *E. coli*. This was attributed to the high uniformity and good dispersion of silver on the surface of the biochar [69]. In a recent study, five gram-negative bacteria—*E. coli*, *Enterobacteria*, *Hafnia*, *Citobacter*, and *Klebsiella*—were eliminated from water using innovative rice-husk biochar supported by iron and copper oxide nanoparticles [70]. For every bacterium examined, a bacterial clearance effectiveness of >92% was documented [71].

The amount of biochar employed, the kind of microbial contamination, its properties, and the concentration of microorganisms in the water all affect how well biochar removes germs from drinking water. Column filtration using charcoal filters has demonstrated greater promise in eliminating *E. coli* from water. According to experiments conducted on both synthetic and natural water samples, 96.6% of the *E. coli* in the water was eliminated by wood waste biochar that was heated to 700°C. Compared to pristine biochar, biochar processed with phosphoric and sulphuric acids eliminated a greater proportion of microorganisms [68]. Although there is little research on the use of biochar to remove microorganisms from water, it is reasonable to infer that the number of microbial pollutants removed from water by biochar may be comparable to that removed from soil [68].

Because of its wide surface area and porous structure, biochar offers more surface-active locations for eliminating microorganisms using a variety of methods. Certain bacterial species' membranes are hydrophobic due to the presence of phospholipids and lipopolysaccharides [15]. *E. coli* attaches itself on charcoal due to hydrophobic interactions. It was discovered that biochar treated with phosphoric acid, sulphuric acid, and potassium hydroxide had greater percentages of *E. coli* elimination [68]. *E. coli* possesses lipopolysaccharides like 2 keto-3-deoxyoctonate carboxylate and phosphoryl, which give the bacteria's membrane phosphate groups and a negative electrostatic surface [72] [73]. *E. coli* was shown to have a tiny positive charge, which was explained by the pH and varying ionic strengths of the solution. Electrostatic deposition is a potential process for bacterial deposition onto charged biochar surfaces, taking into account the positive or negative electrostatic surfaces of bacteria [68]. Derjagui-Landau-Verway-Overbeek (DLVO) theory suggests that bacteria may adhere to biochar surfaces due to repulsive electrostatic interactions and vander Waals forces.

The final firing temperature used during the pyrolysis of the feedstock, the type

of feedstock used to produce the biochar, the type of biochar used—pristine or modified—the presence of interfering concomitants, such as natural organic material (NOM) in aqueous systems, and operating conditions, such as pH, the initial concentration of pathogens, and—most importantly—influent loading rates, all affect how biochar is applied in the remediation of pathogens and indicator organisms in water. There is more room for efficiently optimizing biochars and improving pathogen removal, notwithstanding the variations in microbe removal efficiency of different types of biochars [74].

Because of its adsorption capacity, environmental friendliness, economic viability, and sociocultural acceptability, biochar can be used in microbial remediation. Although the use of biochar in water treatment is growing, the systems still need to be thoroughly developed, improved, and upgraded. Thus far, the use of biochar filtration has mostly been restricted to laboratory settings. It is challenging to forecast the long-term stability of adsorbed pollutants in biochar filters in laboratory-scale trials based on the literature currently available. Long-term monitoring of biochar's adsorption capability and the fate of pollutants it has adsorbed is required. To evaluate biochar's ability to remove microbial pollutants, further research is needed. The decontamination of pathogens like *E. coli* and protozoan parasites has received very little attention. The development of sophisticated biochar treatment methods would help get rid of the inherent pollutants in biochar. An intriguing idea for enhancing biochar's ability to eliminate different pollutants is biochar modification [68].

However, size exclusion is the most popular technique for removing bacteria from water. **Figure 5** below illustrates the various microbe removal mechanisms. The most common methods for removing bacteria from water are straining and hydrophobic interactions, as well as the immobilization and killing of bacteria by silver nanoparticles or silver solution coated on the ceramic water filter walls. Because microbial biofilm forms both within and outside of the micropores, it reduces porosity, which lowers the effectiveness of removing germs from the filtering media. When the size of the bacteria exceeds the filter's pore size, microbial straining retention by straining takes place [75]. Researchers have noted a slight straining impact in eliminating viruses from water; instead, electrostatic interactions between the surface of the biochar and the virus have been identified as the cause of virus remediation. According to earlier studies, biochar made at high temperatures—700°C, for example—has more hydrophobic and steric interactions, which are primarily in charge of the increased elimination of *E. coli*.

With a clearance efficacy of over 75%, biochar has demonstrated encouraging results in the elimination of a variety of microbiological infections, including viruses. According to the authors, the reason for the greater clearance of *E. coli* when compared to bacteriophages is the difference in size. Compared to viruses (like X174), *E. coli* is around 30 times larger. The physico-chemical properties of biochar, initial bacterial concentrations, antecedent dry period, temperature, biofilm formation, occurrence of saturation zone, water chemistry of the influent,

and dissolved organic carbon levels all affect the removal of microbial pathogens using biochar and ceramic water filters [62]. The disinfecting characteristics of biochar doped with metal nanoparticles stop microorganisms from growing and diminish the concentration of microbes in the effluent [65].

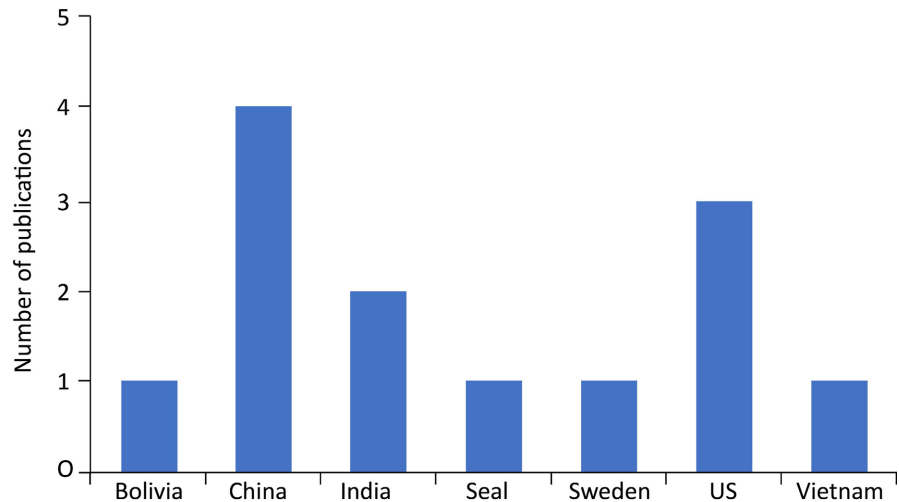


Figure 5. Number of research articles published on biochar filters for removal of microbial pathogens in water in different parts of the world between 2006 and 2022.

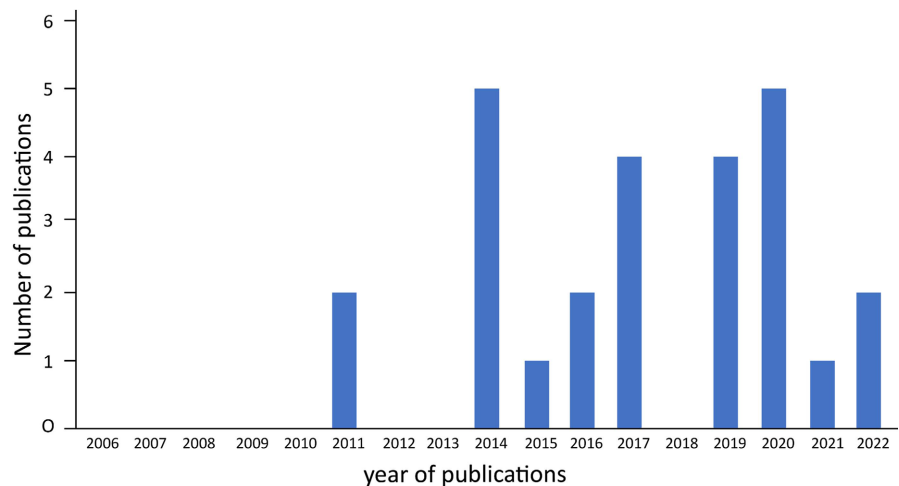


Figure 6. Number of research articles published between 2006 and 2022 on biochar filters for removal of microbial pathogens in water.

Figure 5 illustrates that no African nation made any contributions to the study of biochar filters for the elimination of contaminants from drinking water. The United States and China, two industrialized nations, were the focus of the research. Because these nations can afford more costly and effective water treatment methods, the use of biochar technologies is limited to research labs. According to the figures, African academics who ought to be leading the charge on low-cost water treatment technologies that are better suitable for their home nations, which possess the natural resources needed to produce the feedstocks needed to make

biochar, are lacking motivation. **Figure 6** illustrates how few research articles there are on biochar filters for water treatment, with only five publications published between 2014 and 2020. Year 2006 to 2010, 2012, 2013 and 2018 no research work was published on biochar filters. More work therefore needs to be done particularly in Africa by African researchers so that local populations may actually embrace the POU technology and implement it in their households as a way of reducing waterborne diseases and also reducing costs in acquiring safe drinking water.

13. Perspectives

The majority of studies on filtering out microorganisms from water have concentrated on eliminating indicator pathogens, primarily *E. coli*. Future research should concentrate on measuring and eliminating other microbiological pathogens (viruses, bacteria) and protozoa from drinking water. The removal of *E. coli* from storm waters has been extensively documented by numerous studies; nevertheless, there is a dearth of literature on the removal of microbiological pathogens from drinking water. The majority of earlier research was conducted in labs using short-term column/microcosm studies with sand and biochar filters. However, long-term pilot and field-scale studies should be conducted based on the experiment results to evaluate the biofilters' performance under various environmental, hydraulic, and water chemistry conditions [62]. Information on impact of physicochemical properties of biochar and ceramic water filters such as feedstock type, biochar particle size, clay particle size, surface area, pyrolysis conditions, ceramic water filter fabrication techniques, impact strength, biochar and ceramic filters modification on the removal capacities of microbes. The above-mentioned research areas require more exploration so as to help design high efficiency biochar and ceramic water filters ideal for removal of multiple pollutants in a single filtration run.

14. Future Prospects for Combined Ceramic Water Filter-Biochar Technology in Drinking Water Treatment

Combining the two technologies into a single unit as shown in **Figure 7** for point-of-use water treatment, appears to be feasible given the benefits of using ceramic water filters and biochar filters for the removal of microorganisms in water as reported in the literature. This is because the effectiveness of ceramic water filters and biochar filters is well established. When the two methods are combined into a single unit, as illustrated in the figure, they will enhance one another. When filtering water from contaminated sources, one method may make up for the drawbacks of the other. It has been demonstrated that altering ceramic and charcoal filters increases their capacity to remove pollutants. It is necessary to investigate the use of the biochar-ceramic filtering unit on a large scale.

Microbial removal efficiencies should be optimized, flow rate of the filtration unit should be economically sustainable. More work needs to be done in evaluating

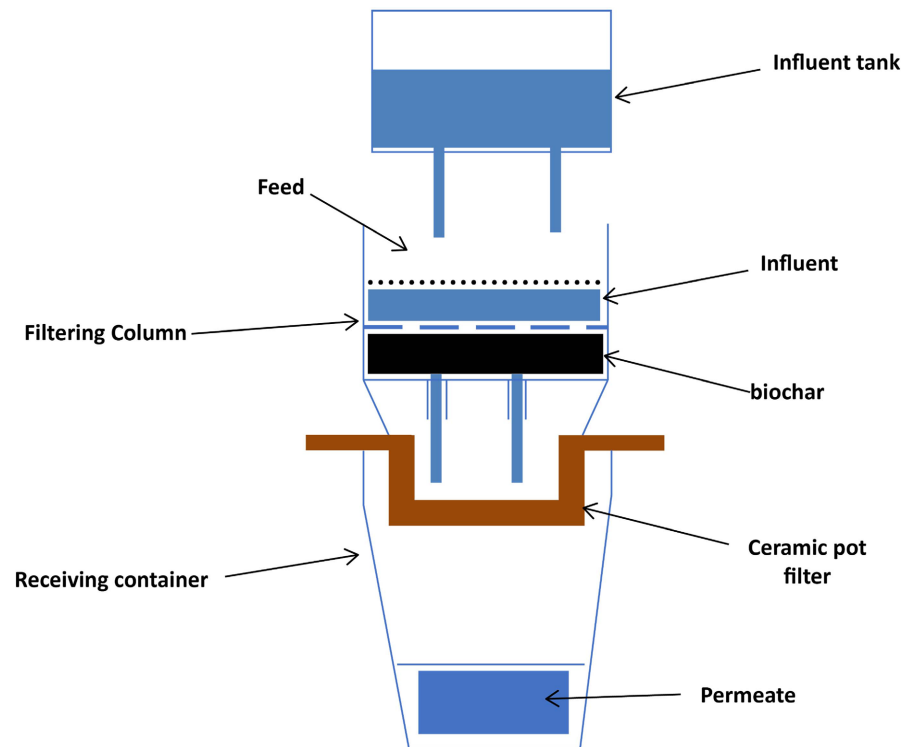


Figure 7. A futuristic biochar and ceramic filters unit for gravitational filtration.

the capabilities of biochar and ceramic filters in removing or reducing pathogens such as *E. coli* and many other diseases causing bacteria. In the battle to eradicate waterborne illnesses in rural and semi-urban areas of poor nations as well as disaster-affected areas, POU filters (ceramic and biochar) represent a sustainable water treatment technology. According to reports, POU filters are six times more cost-effective than centralized water distribution systems and can potentially minimize environmental consequences like global warming by up to 75% [45]. By improving filter fabrication, cutting costs, and utilizing eco-friendly materials and processes—such as recycled materials like paper fiber, municipal sewer waste, sawdust, rice husks, and starch, to name a few—the environmental impact and footprint of ceramic and biochar filters can be improved [20].

15. Limitations from the Reviewed Studies

In reviewing the literature, it appears there are gaps and missing information. For instance, some studies differ when it comes to biochar type, feedstock source, and particle size so that comparability between different studies is elusive, making it difficult to ascertain the claim of biochar being efficient in water filtration. Moreover, most studies provide insights on the removal of *E. coli* using biochar as the process of removal. However, the mechanisms provided to explain the removal processes have differing views from pore straining to electrostatic forces. This disparity surely could arise from the more intricate relationship existing between biochar and bacteria and the possibly dominating role of other environmental con-

ditions.

The review of literature uncovered another gap, which is the absence of uniformly accepted methods for determining the efficiency of bacteria removal in a biochar water filtration system. This poses challenges in attempting to reconcile the findings of various studies and establishing guiding principles for effective design and function of biochar filtration systems. Furthermore, most studies have a narrower scope that is limited to lab scale experiments, which often do not consider different biofilm flow rates, water quality, or even biofilm age. The literature review gives some indication on what could explain the performance of biochar in water filtration, notably type of feedstock used, the conditions of pyrolysis, and the different traits of bacteria. Still, this is not exhaustive and further investigation is needed to resolve these gaps and inconsistencies.

To start with, while removal of bacteria by biochar has been attributed to hydrophobic interactions or electrostatic deposition, little is known about the specific context in which these processes take place. This would need to be explored further. Next, biochar's aid in microbial removal is moderated by its virus clearance capability, which can be of a striking 75%. Interpretation of these results, however, can be problematic. For example, the varying impact of NOM (natural organic matter) on the microbial removal achieved by biochar is still unknown and could cloud the results.

Biochar's influence on the removal of microorganisms, including viruses, with a striking effective rate of over 75% clear is suggested in the review. For better understanding, however, the unique dimension of the whole putative difference between *E. coli* and bacteriophages inclusive of the size factor could risk removal efficiency and thus generalization of results to other microbial species and their relatives. Secondly, such biochar characteristics, initial concentrations of microbes, antecedent dry periods, and water chemistry that have been shown to influence microbial removal efficiency suggest that their biochar disinfection mechanisms methyl and their interactions with different environmental variables need to be better understood.

Another limitation of this review is the greater emphasis on laboratory-scale studies when compared to field or industrial scale studies. This lack of emphasis makes it challenging to determine the usefulness of biochar as a water filter in practical scenarios that involve changes in flow rate, biofilm development, and water quality dealing with, or in fact, once the filter has been deployed. Also, there seems to be insufficient literature regarding the use of biochar filters for the removal of some pathogens such as *E. coli* and protozoan parasites, pointing to the necessity of more focused studies on these pathogenic organisms.

16. Conclusion and Recommendation

It must be noted that Contaminated water spreads over 80 diseases, impacting economic progress and health. Intestinal bacteria cause most disease outbreaks; 88% of diarrheal illnesses stem from poor hygiene. Over 40% of the global popu-

lution lacks access to clean water and sanitation. Waterborne parasites cause significant suffering in both developed and developing nations. Microorganisms can be eliminated through chemical or physical methods. Physical methods include filtration and distillation; chemical methods include chlorination and ozonation. UV light can lead to microbial regrowth; membrane filtration is effective but costly. Thus, further detailed studies must be conducted specifically looking at the specific pathogens, bacterial and chemical water purification.

There is a need for further study to discuss the mechanisms by which ceramic and biochar filters remove pathogens, it does not delve deeply into the specific interactions at the molecular level. This also results in the need for implementation of these filters so that studies can be conducted on their efficiencies and durability so that this information can be available since it does not exist.

The study aims to promote low-cost biochar and ceramic filters for pathogen removal. The review addresses a critical global health issue: access to safe drinking water. It focuses on affordable and sustainable POU treatment technologies relevant to developing countries. The potential of a hybrid biochar-CWF system, although not yet extensively researched, offers a novel approach to water purification and warrants further investigation. There is need for further study on the effectiveness of ceramic and biochar filters in developing countries since biochar and ceramic filters have not yet been used much, if used at all, in developing countries.

Both ceramic and biochar water filters are popular, affordable, and effective methods of treating drinking water. Traditional water treatment methods including carbon nanotubes, activated carbon, and ion exchangers can be readily replaced by the less expensive methods. Despite the fact that ceramic water filter technology has been gaining popularity in research applications, no information about combining ceramic water filters with biochar for drinking water treatment—specifically, the removal of microbiological contaminants—has been published. As was mentioned above, there is a plentiful supply of locally accessible feedstock for the production of ceramic water filters and biochar filters. In low-income nations, the filters are perfect for point-of-use home water filtration.

However, the emphasis placed on low-cost biochar filters for addressing water pollution overlooks the more complex sociocultural and ecological issues that would arise if these technologies were deployed. Even in socioeconomically disadvantaged communities, adoption may prove difficult due to limited funding for initial expenditures, maintenance, and material resources. Moreover, ensuring that these technologies achieve a net positive impact requires biochar and material sourcing sustainability, filter impact over time, lifecycle disposal, and other encompassing environmental assessments. This demonstrates the need for further research pertaining to biochar water purification filters in Africa as well as other developing nations.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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