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A Critical Review of Water Filtration Methods in Developing Countries

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Abstract: Access to clean and safe drinking water remains a critical challenge in various developing countries, where water sources are frequently contaminated with pathogenic microorganisms and chemical pollutants such as coliform bacteria, arsenic, and fluoride. These contaminants contribute significantly to the spread of waterborne diseases and related health conditions. This review presents a comparative analysis of household- and community-scale water filtration methods, focusing on their applicability, efficiency, and sustainability in low-resource settings. Conventional sand and bio-sand filters demonstrate bacterial removal efficiencies of 85–98%, while riverbank filtration systems can reduce coliform counts by 2–4 log units but are less effective against dissolved arsenic and fluoride. Emerging low-cost technologies, such as filters composed of plant biomass with fluoride removal efficiency up to 70%, zeolite-based media with arsenic removal ability exceeding 90%, and silver-impregnated porous clay pots with >99% of bacterial inactivation efficacy, are examined for their potential to improve water quality with production costs as low as US $2-5 per unit and sustainability. Further, the article evaluates these methods based on key criteria, including technical feasibility, contaminant removal efficiency, environmental impact, and ease of implementation. The novelty of this review lies in its integrated approach to offer a critical perspective on both conventional and alternative filtration systems within the specific socio-economic and environmental contexts of developing regions. This work contributes valuable insights toward the development of effective, scalable, and community-appropriate water treatment technologies by highlighting both their limitations and opportunities for innovation.

Keywords: Water filtration; household sand filters; household bio-sand filters; water treatment system; riverbank filtration

1. Introduction

In recent decades, significant progress has been made in the development and enhancement of water treatment technologies, particularly in filtration methods [1, 2]. Innovations in filter design, coupled with the availability of a wide range of chemical coagulants, have enabled the implementation of filtration systems that operate without traditional sedimentation processes [3]. Direct filtration systems are characterized by including only preliminary screening, coagulant dosing, rapid mixing, and flocculation, eliminating the need for sedimentation [4]. However, a key limitation of these systems is their typically insufficient solid-holding capacity, rendering them less effective under sustained conditions of high turbidity [5].

In France, systematic patent protection for filtration technologies became feasible after the patent law of 1791, which enabled the commercialization of systems using sponges, charcoal, wool, sand, crushed sandstone, and gravel [6]. By the early 1800s, England and Scotland initiated large-scale surface water filtration through engineered systems, with London pioneering municipal applications [7]. Engineers experimented with diverse configurations, including downward, upward, and horizontal flow; graded sand and gravel media (finer to coarser); and backwashing via reverse flow [8]. In 1829, James Simpson's landmark slow sand filter (SSF) for Chelsea Water Works featured an underdrain system, graded gravel-sand media, and an SSF system to purify the water [9]. SSF, first implemented in the U.S. at Poughkeepsie, New York (1872), originated from European designs, such as James Simpson's system in London [10]. Remarkably, these core design principles of filtration, including biological filtration layers, graded media, and low flow rates, remain fundamental to modern SSF systems [11]. The reliance of these filtration approaches on natural processes, minimal chemical input, and low maintenance makes them significantly relevant for developing countries in recent times, where cost, simplicity, and sustainability are crucial for household- and community-scale water treatment. Hence, the World Health Organization has recognized SSF as one of the most cost-effective methods for small communities that are capable of achieving 90-99% of pathogen removal without complex infrastructure [12-14]. Thus, the historical evolution of filtration systems provides a valuable foundation for addressing current challenges in low-resource regions.

The essential filter design principles are vital since the filter is used to remove pathogenic waterborne microorganisms, including bacteria, viruses, and protozoan parasites, that pose significant risks to drinking water safety when barriers are breached [14]. Among these microorganisms, viruses are particularly challenging due to their small size and resistance to conventional disinfection (e.g., chlorine) [15], necessitating multi-barrier protection and rigorous monitoring of removal efficiency across treatment stages [16]. Besides, a parallel concern is eutrophication from nutrient pollution (e.g., nitrogen/phosphorus), which drives the proliferation of toxin-producing *cyanobacteria* [17]. While ancient *cyanobacteria* generated Earth's oxygen, modern blooms in nutrient-rich waters release cyanotoxins (e.g., microcystins) that threaten aquatic ecosystems, livestock, and human health [18, 19]. Consequently, wastewater discharge into surface waters requires dual treatment objectives, including advanced nutrient removal to curb eutrophication and robust disinfection to inactivate pathogens.

SSF that spread to communities, such as Lawrence and Massachusetts (USA), has effectively eliminated microorganisms through biological activities in the *schmutzdecke* layer [20]. However, SSFs possess limitations, which include the tendency to clog over time and the requirement of frequent maintenance [21]. The limitations of SSF, particularly its inability to meet the demands of highly turbid water and rapid urban consumption, have contributed to its reduced use in favor of rapid sand filtration systems, which integrate coagulation and a mechanical backwashing approach to enhance efficiency and adaptability in modern water treatment contexts [22]. Despite this, SSF remains critical in niche applications, particularly in low-resource settings, due to its robust pathogen removal without chemical inputs.

Post-Civil War America started with SSF, rapidly adopted efficient rapid sand filters, and later entered the modern era of safety with chlorination in the year 1908 [23]. The 20th century has witnessed rising consumer expectations for better water quality and government regulations (for instance, the Safe Drinking Water Act (SDWA)), which drive continuous improvement to address a broader spectrum of contaminants. Comprehensive federal regulation was initiated with the Surface Water Treatment Rule (SWTR) in 1989, which mandated filtration and disinfection for U.S. public water systems using surface water sources [24]. This rule specifically addresses pathogens, such as *Giardia lamblia* and *Cryptosporidium*, which provide protozoan resistance to conventional disinfection (e.g., chlorine) and require physical removal through filtration [25]. Driven in part by the *Cryptosporidium* outbreak in Milwaukee, USA (year 1993), subsequent regulations such as the Interim Enhanced Surface Water Treatment Rule (IESWTR, 1998) and the Long Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR, 2006) imposed stricter turbidity standards and risk-based treatment requirements, thereby compelling several unfiltered systems to implement filtration for complying with the enhanced microbial protection standards [26]. Therefore, filtration remains an essential process in surface water treatment, playing a vital role in the effective removal of microbial contaminants and the protection of public health.

Besides the microbial contaminant removal, the Langat River in Malaysia was identified to have distinct elemental distributions, which include heavy metals, such as arsenic (As), copper (Cu), chromium (Cr), nickel (Ni), lead (Pb), and zinc (Zn) [27]. Before water is consumed by a human's body, these harmful impurities, which are highly toxic compounds in the water, must be removed [28]. These trace elements showed higher prevalence in suspended solids, whereas sediments exhibited elevated concentrations of Zn, Ni, Pb, and Cr [29]. Elemental analysis was performed using inductively coupled plasma mass spectrometry (ICP-MS) for water, suspended solids, and sediment samples [30]. Also, besides removing microbial contaminants, the efficiency of the removal of these heavy metal pollutants is essential [31, 32]. Despite evidence of heavy metal pollution, comprehensive studies on filtration efficacy for these contaminants, especially REEs, are still absent in the literature.

On the other hand, short-term surface water pollution from elevated heavy metal concentrations is predominantly driven by industrial and agricultural anthropogenic activities, including mining operations, coal combustion, battery manufacturing, chemical production, and improper waste disposal [33]. While ecosystems possess limited adaptive capacity to naturally occurring geological weathering of heavy metals, anthropogenic inputs frequently exceed tolerable ecological thresholds and disrupt biogeochemical cycles [34]. Heavy metals and metalloids are prioritized concerns due to their persistence, bioaccumulation potential, and acute-to-chronic toxicity in aquatic ecosystems and human health (e.g., renal failure, carcinogenicity) [35]. Household-scale water filtration systems, due to the risks of heavy metals, offer a practical interim solution for improving water quality through low-cost, energy-efficient contaminant removal [36]. However, comprehensive analyses of filtration technologies remain scarce, particularly regarding long-term efficacy, scalability, and trade-offs between conventional and advanced methods.

This narrative review aims to evaluate household filtration technologies with emphasis on bio-sand, ceramic, and composite media as sustainable point-of-use solutions for resource-limited settings. Unlike previous reviews that often focus solely on technical performance, this work uniquely emphasizes household- and community-scale filtration technologies while integrating both social and technical dimensions within the context of developing countries. Further, this review quantifies contaminant removal efficacy for priority pollutants (pathogens, turbidity, heavy metals), benchmarks socio-technical trade-offs (comparison between cost and performance, as well as local adaptability and reliability), and identifies implementation barriers across diverse hydrogeological and cultural contexts, through integrated analysis of peer-reviewed literature, experimental data, and analytical modeling approaches. While these systems offer critical advantages, including zero energy requirements, minimal sludge generation, and construction from local materials, which improves their performance, variability underscores an urgent need for standardized testing protocols, context-specific design optimization, and resolved scalability gaps. Thus, this review establishes the recent studies that accelerate the deployment of effective, equitable water filtration in global communities, where centralized filtration treatment remains limited. For this narrative review, relevant studies were retrieved from Google Scholar and Web of Science, covering literature published between 2004 and 2025.

2. Water Filtration and Coagulation

Water is a fundamental human right and essential for life, which requires safety, accessibility, and adequate treatment to meet health and societal needs [37]. Globally, half of the 700 million people lack safely managed drinking water services, while approximately 2 billion people use water contaminated by feces [38]. Recent statistics have projected that global water demand will surge, driven by agricultural intensification, population growth, and industrialization [39]. Contaminated water transmits diseases, such as cholera and typhoid, accounting for annual deaths, underscoring the critical need to eliminate pathogens (viruses, bacteria, and protozoa), micropollutants (pesticides, pharmaceuticals), and geogenic toxins [40]. Furthermore, the chemical contaminants, including As (carcinogenic), Pb, Cr, Cd, Ni, and fluoride (skeletal/dental fluorosis), are widely reported across different regions of the world [41], posing significant global concerns for human health and water safety.

In the agro-food and beverage industry wastewater treatment, raw materials, such as fruit pulps (guava, orange), sugars, and phosphates, contribute to high organic loads (Biochemical oxygen demand (BOD)/chemical oxygen demand (COD)) and suspended solids (SS), necessitating robust pre-treatment [42]. Coagulation-flocculation is commonly employed to remove SS and colloidal organic matter and usually reduces the load on downstream biological systems [43]. Further, coagulants (e.g., ferric chloride) neutralize particle charges to destabilize colloids, while flocculants (e.g., polymers) bridge particles into settleable flocs. These flocs are subsequently removed via a sedimentation or filtration process, which significantly reduces turbidity and organic content before biological treatment. However, using chemical coagulants and synthetic flocculants can cause problems, such as producing too much sludge, creating secondary pollution, and increasing costs. This shows the need for greener options, like bio-based coagulants or combined treatment methods.

Numerous studies have examined the efficiency of coagulants (e.g., ferric chloride, poly-aluminum chloride) and flocculants (e.g., polyacrylamide, chitosan) in industrial wastewater treatment [44]. Key factors include coagulant dosage, pH adjustment, and flocculant addition sequence, which dictate charge neutralization, sweep-floc mechanisms, and floc aggregation kinetics [45]. In municipal wastewater treatment, granular activated carbon (GAC) effectively absorbs COD and volatile organic compounds (e.g., benzene) by leveraging its porous structure and surface functional groups [46]. However, optimal coagulation conditions for turbidity, natural organic matter, or color removal often diverge from those targeting natural organic matter (NOM) due to differences in NOM hydrophobicity, molecular weight, polarity, acidity, and charge density [47]. While baseline coagulation prioritizes turbidity reduction through particle destabilization, optimized coagulation requires precise adjustments in dosage and pH to enhance NOM removal, particularly hydrophobic fractions, such as humic acids, which reduce disinfection by-product (DBP) formation potential [48].

Water filtration removes suspended particles (e.g., silt, algae), microorganisms (bacteria, protozoa), and targeted chemical contaminants to produce water with specific quality standards (e.g., drinking, pharmaceutical) [49]. Conventional drinking water systems employ multi-barrier processes that are adapted to source water quality, which typically integrate coagulation, granular media filtration, disinfection [50], and optionally membrane filtration or adsorption, that is not a rigid five-stage sequence. Nonwoven membranes (melt-blown, spun-bonded, and electrospun nanofibers) enable effective microfiltration (0.1–10 μm pore size) for particle removal, with hybrid micro- or nano-fiber composites enhancing selectivity [51]. Moreover, the traditional additives (e.g., bentonite clays, polyanionic cellulose) undergo thermal degradation and polymer chain scission to reduce fluid-colloidal stability [52]. While thermal expanders mitigate this thermal degradation partially, nanoparticle reinforcements, such as Nano Glass Flakes (NGFs), demonstrate superior performance, including reduced fluid loss and enhanced rheology with higher yield points or gel strength [53]. Nanoparticles achieve a higher yield point or gel strength by forming tortuous pathways that restrict fluid invasion while maintaining mud workability [54]. Besides tough conditions like drilling, the use of nanomaterials can also help in potable water treatment applications. They work in similar ways, such as making water flow through longer paths, keeping the system stable, and removing more contaminants. The following sub-sections present different filtrations.

2.1. Electrospun Polyacrylonitrile Nanofibrous Membrane Filtration

Polyacrylonitrile (PAN), a synthetic polymer composed of repeating acrylonitrile units, is a dominant precursor for carbon-based materials due to its high carbon yield [55], superior mechanical strength (high tensile strength in carbonized form), and exceptional thermal stability [56]. These properties stem from PAN's stereospecific molecular structure and high nitrile-group density, which facilitate cyclization and ladder-polymer formation during stabilization. However, unmodified PAN exhibits inherent hydrophobicity, or so-called not excellent water wettability, due to the presence of nonpolar nitrile groups, limiting its filtration applications without surface modification or blending of composites.

Electrospinning, which is a scalable nanofiber production technique, leverages electrostatic forces to generate a polymer-solution jet from a Taylor cone, forming continuous fibers [57]. This electrospinning process is particularly critical for PAN-based materials, enabling tunable fiber morphology through parameters, such as solution viscosity (e.g., Dimethyl Sulfoxide (DMSO) or Dimethylformamide (DMF)) and voltage [58, 59]. PAN nanofibers synthesized via the electrospinning method serve as foundational substrates for high-performance applications, including oil or water separation membranes [60] (e.g., PAN or halloysite composites achieving high flux recovery), carbon nanofiber precursors [61], and flame-retardant materials (limiting oxygen index) [62].

Electrospun PAN or halloysite nanotube (PAN/HNT) composite membranes demonstrate exceptional oil/water separation efficiency to achieve high removal of oil-in-water emulsions [63]. The incorporation of HNTs has been identified to enhance membrane hydrophilicity for boosting pure water flux while maintaining high oil rejection [64]. This performance stems from HNTs' nano-tubular structure to form preferential water pathways and surface charge modifications [65]. Electrospinning refined origins enable precise fabrication of PAN/HNT nanofibers with tunable diameters, ultrahigh surface-area-to-volume ratios, and interconnected porosity [57]. These composites synergize PAN's mechanical robustness with HNTs' thermal resilience and ion-exchange capacity [66]. The resultant membranes exhibit polymer advantages (e.g., moldability and corrosion resistance), and inorganic advantages (e.g., mineral rigidity and chemical inertness), making them ideal for harsh-environment separation applications [67]. Emerging contaminants such as Per- and polyfluoroalkyl substances, microplastics, and pharmaceuticals pose additional challenges for water treatment in harsh environments [68-70].

PAN-based nanofibers are extensively utilized in advanced water purification membranes due to their high surface area-to-volume ratio, tunable pore size, and controllable hydrophilicity [71]. These properties are optimized through electrospinning parameter adjustments (e.g., voltage, flow rate, collector distance) to achieve the desired porosity and fiber morphology [72]. PAN nanofiber membranes are primarily applied in ultrafiltration (UF) and nanofiltration (NF) systems for pollutant removal [73]. Graphene oxide (GO) composites significantly enhance membrane performance. For instance, Ag/GO-PAN nanofibers achieve 30% higher water flux, compared to unmodified PAN, while improving antibacterial efficiency against *S. aureus* [74, 75].

Historically, PAN was used in textiles to produce wool-like fibers via wet or dry spinning; however, its dominant modern application is carbon fiber production through stabilization and carbonization [76]. Additional PAN's functional uses include filtration systems (e.g., oily wastewater treatment via hydrolyzed PAN-TiO_2 membranes) [77], cement reinforcement (e.g., enhanced concrete durability through nanofiber integration) [78], acoustic/thermal insulation (e.g., leveraging high porosity and mat flexibility) [79], and heavy metal adsorption.

Despite these advantages, electrospun PAN or PAN/HNT nanofiber membranes face challenges in scalability and cost compared to conventional phase-inversion polymeric UF and NF membranes. Electrospinning requires high-voltage setups and often low-throughput processes, which limit their large-scale production [80]. Conventional UF/NF membranes, by contrast, are cheaper, with a production cost of ~\$0.1-0.5 per m^2 and are already industrially mature, though they often suffer from fouling and limited chemical resistance [81]. PAN/HNT composites show superior flux and oil rejection (>98%) [82]; however, their fabrication costs and material integration, such as halloysite source and nanofiber uniformity, remain higher than commercial UF membranes. It is noteworthy that PAN-based systems exhibit higher reusability and longer lifetimes under harsh environments compared to polymer-only membranes, suggesting better long-term sustainability in niche, high-demand applications [83].

2.2. Riverbank Filtration

Riverbank Filtration (RBF) is a natural pre-treatment method where surface water infiltrates through aquifer sediments (e.g., sand/gravel) [84] before extraction via wells that have been deployed globally for over a century to augment drinking water supplies [85]. Sustainable RBF operation requires maintaining stable hydraulic conditions and water quality compliance (e.g., pathogen/log reduction targets), which directly influence downstream treatment design [86]. The process leverages hyporheic exchange, including river percolation, attenuation of contaminants via physical filtration, biodegradation (e.g., organic pollutant breakdown in oxic zones), and sorption (e.g., heavy metals onto clay or iron oxides) [87]. In losing streams (common in arid regions), water loss to aquifers enhances RBF filtration residence time to improve contaminant removal efficiency [88]. Under optimal conditions (e.g., minimal aquifer pollution), RBF-produced water can exceed local groundwater quality with high *Cryptosporidium* removal, Dissolved Organic Carbon (DOC) reduction, and heavy metal attenuation [89]. **Figure 1** summarizes the critical RBF design parameters.

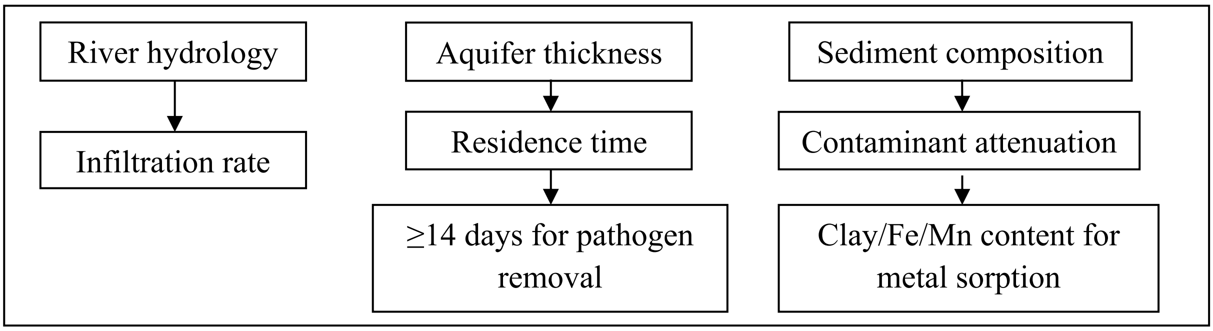

Figure 1. Critical RBF design parameters

RBF has been utilized in Europe for over 150 years along major rivers, such as the Rhine (Switzerland and Germany), Danube (central and southeastern Europe), and Elbe (Germany and the Czech Republic), with documented implementation in Düsseldorf, Germany, since 1870 [89, 90]. In the United States, RBF has been operational for several years in key sites, such as the Ohio River in Kentucky and the South Platte River in Colorado, where it serves as a cost-effective pretreatment technique to reduce pathogen loads [91]. The process leverages natural attenuation mechanisms such as filtration, biodegradation, and adsorption that are within aquifer sediments to eliminate more than 90% of turbidity and significantly reduce *Giardia*, *Cryptosporidium*, and viruses [92]. Recent applications in Egypt demonstrate RBF's adaptability to diverse hydrogeological settings, though site-specific challenges, such as manganese mobilization (e.g., in Luxor, Egypt), require supplemental treatment [88].

2.2.1. Comparisons Between Riverbank Filtration and Slow Sand Filtration

The cholera epidemic in Hamburg, Germany, in 1892, which was caused by *Vibrio cholerae* contamination of the Elbe River, resulted in approximately 10,000 deaths and exposed critical failures in municipal water management [93]. Unlike other European cities that had implemented filtration systems, Hamburg's merchant-led government had refused to treat its water supply, prioritizing economic interests over public health. In response, Hamburg abandoned direct river intake and rapidly constructed a mechanical sand filtration plant by 1893, not a subsoil passage, which became operational a year ahead of schedule. This system reduced turbidity and pathogens through engineered granular media, without standalone natural subsoil filtration.

While SSF and RBF both leverage biological and physical attenuation mechanisms, their operational principles differ substantially [94]. SSF relies on a cultivated *schmutzdecke* (biological layer) for pathogen elimination [95]. RBF depends on aquifer properties (e.g., sediment mineralogy, residence time) for contaminant degradation to achieve pathogen reduction [94]. Both methods provide robust pathogen removal but are typically integrated with advanced processes to meet modern standards; instead, they often integrate with advanced processes (e.g., chlorination, membranes) to meet regulatory standards [96]. Moreover, site selection hinges on hydrogeological feasibility, infrastructure costs, and maintenance complexity, with residence time requirement in RBF for optimal efficacy, and the need for periodic sand scraping in SSF [88].

The SSF treatment of water by percolation through a biologically active sand bed has been identified to optimize elimination of pathogens [11]. This process functions as a fixed-bed bioreactor, relying on a microbial biofilm (*schmutzdecke*) and subsurface biological layers to achieve removal of bacteria, protozoa, and viruses, reduction of biodegradable organics (e.g., DOC), and near-complete turbidity elimination (<1 Nephelometric turbidity units (NTU)) [97]. While robust against moderate pH fluctuations and low surfactant levels, SSF is vulnerable to extreme pH, which degrades biofilm integrity, high metal concentrations cause pore clogging, and cold temperatures slow down their biological activity [98]. In wastewater applications, SSF serves as tertiary treatment for septic tank effluent polishing (BOD_5 reduction) before soil dispersal, anaerobic effluent post-treatment (e.g., anaerobic up-flow sludge blanket (UASB) reactors) to achieve pathogen removal, and water reuse systems when combined with UV disinfection [99].

In SSF, a biologically active layer (*schmutzdecke*) is formed at the sand surface, which comprises bacteria, protozoa, and extracellular polymers [95]. This layer physically traps suspended solids (turbidity reduction) and biologically degrades organics via extracellular enzymes (BOD_5 removal), and adsorbs pathogens (*E. coli* reduction) [11]. Hydraulic conductivity decreases during the accumulation of contaminants, which requires periodic scraping of the *schmutzdecke*. Likewise, regeneration requires 4–11 days to re-establish microbial communities [100]. Post-maintenance efficiency is typically improved due to renewed biological activity. However, fundamental RBF operates differently from SSF, as it does not involve the formation of a surface *schmutzdecke* [84]. For instance, biofilms coated sediment grains throughout the hyporheic zone, and contaminant removal occurred via aerobic/anaerobic biodegradation in subsurface biofilms, mineral sorption (e.g., Fe/Mn oxides adsorbing metals), and straining in sediment pores. Moreover, high-flow events may scour riverbed sediments, however they do not eliminate subsurface biofilms, which persist in aquifer matrices.

2.2.2. Removal of Pathogens, Indicators, Surrogates, and Toxins by Using Riverbank Filtration

RBF is a natural water treatment process where surface water infiltrates through a riverbed or bank sediments into an aquifer, driven by natural hydraulic gradients or pumping-induced drawdown [101]. During subsurface passage, water undergoes contaminant attenuation via pathogen removal and biodegradation of organic compounds (e.g., DOC reduction) [102]. It is noteworthy that the pathogen removal includes the physical straining of particles (e.g., *Cryptosporidium*), adsorption to clay or iron oxide coatings on sediment grains, and die-off/predation in biofilms (reduction for bacteria/viruses) [103]. Meanwhile, optimal RBF requires aquifer granulometry such as sandy sediments with hydraulic conductivity and flow velocity to ensure more than 14-day residence time, and clogging control, such as riverbed turbidity of <50 NTU to maintain infiltration rates [89]. Additionally, pathogen attachment depends on grain surface charge (e.g., Fe/Mn oxides favor adsorption) and pore geometry (tortuosity of >1.5 enhances contact). The detachment is negligible under stable flow, which is increased during rapid pumping surges or the riverbed scouring process. The LT2ESWTR was applied to all U.S. public water systems (PWSs) using surface water or groundwater under the direct influence of surface water (GWUDI), with GWUDI status requiring hydrogeological verification of hydraulic connectivity [86]. This regulation, which was established in 2006, targets *Cryptosporidium* risks through risk-based treatment requirements, where source water monitoring is mandatory for *Cryptosporidium*, *E. coli*, and turbidity.

2.3. Removal of Fluoride, Coliform Bacteria, and Arsenic by Filter Media

The challenge of the fluoride, coliform bacteria, and arsenic removal disproportionately affects small, remote communities reliant on groundwater, where exposure to As above 10 μg/L causes carcinogenic (skin/lung/bladder cancers), cardiovascular, and dermal effects [104]. Thermotolerant coliforms (e.g., *E. coli*) indicate fecal contamination, signaling potential pathogens (viruses, protozoa) that can cause acute gastroenteritis (vomiting, cramps, diarrhea) and chronic conditions, such as kidney failure [105]. While household SSFs offer low-cost treatment, their unmodified designs exhibit limitations [106]. These limitations of

SSFs include pathogen removal and reduction (insufficient for highly contaminated sources), chemical ineffectiveness, where near-zero removal of dissolved As/fluoride has led to As removal via adsorption, and pathogen reduction while maintaining affordability [106].

2.4. Low-Cost Household Drinking Water Filtration System

Mahmood [107] evaluated a low-cost HSF for treating contaminated drinking water in earthquake-affected communities of northern Pakistan, where over 4,000 water systems were damaged. Two villages were selected for field demonstrations, with HSF performance monitored through microbiological testing (pre-treatment with 101 CFU/100 mL of *E. coli* and 73 CFU/100mL of total coliforms) and community engagement (focus groups and questionnaires assessing water quality perceptions). The HSF used a concrete or plastic container (standard height: ~0.9 m) filled with locally sourced and graded sand as well as gravel layers (not cylindrical pipes), to achieve a 97% reduction in *E. coli*, coliforms, and turbidity after 10 days of operation, and 67% of community acceptance, with turbidity identified as the primary water quality. While HSF effectively addressed immediate disaster recovery needs, recent advances in gravity-driven membrane (GDM) filtration offer complementary solutions for sustainable water treatment [108]. GDMs use ultra-low-pressure membranes (e.g., PVDF hollow fibers) to achieve 2–4 log pathogen removal with minimal maintenance, showing promise for rural and emergency contexts. However, the latest review on low-cost GDM for sustainable water treatment by Nguyen [109] summarized the recent advantages and limitations of GDM. Compared to conventional filters like HSF, BSF, and BSZ-SICG in terms of cost and maintenance, GDM filtration has a high initial cost, but it is technologically superior in terms of treatment quality and eliminates the daily and weekly maintenance burden. Even the conventional filters are cheaper, but their long-term effectiveness is notoriously variable due to their dependence on perfect user behavior.

2.4.1. Household Bio-sand Filter using Plant Biomass

Baig, Qaisar Mahmood [102] demonstrated that decentralized household water treatment, particularly biosand filters (BSFs), offers a practical solution for low-income communities that lack safe drinking water access [110]. BSFs significantly reduce diarrheal diseases and improve water quality by treating water at the point of use [111]. Globally, over 300,000 BSFs have been installed across 69 countries to serve approximately 1.5–2 million people [112]. Field studies confirm BSFs achieve 1–3 log high removal of *E. coli* and thermotolerant coliforms, high turbidity reduction, and high user satisfaction in sustained deployments. These systems are low-cost, simple to operate, and maintainable with local materials (gravel, sand) [113]. Baig, Qaisar Mahmood [102], developed a modified BSF incorporating coniferous Pinus bark biomass (CPBB) to address severe bacteriological contamination in earthquake-affected northern Pakistan. This amendment enhanced pathogen removal through adsorption while reducing filter weight, showing their advantages in mountainous terrain. Four prototype filters that are field-tested under temperate conditions show 97% *E. coli* removal after 10 days of operation, despite cold-climate biological activity limitations.

2.4.2. Nanofiltration and Reverse Osmosis

RO and NF are pressure-driven membrane technologies that remove dissolved salts and divalent ions via semi-permeable barriers [114]. State-of-the-art membranes utilize crosslinked aromatic polyamide (PA) active layers formed by interfacial polymerization on polysulfone (PSU) support as a standalone material [115]. Recent innovations explore alternative selective layers, including GO laminations [116], aquaporin-embedded block copolymers [117], and liquid crystal-templated nanopores [118]. In this section, the emerging materials' scalability, fouling resistance, and commercial viability, with RO-specific economic analyses comparing energy savings, are evaluated.

PA-based membranes operate via solution-diffusion mechanisms, requiring pressures greater than osmotic pressure [119]. Their performance is dynamically influenced by feeding temperature, pH, and ionic composition. PA's nanoscale heterogeneity complicates direct characterization; pore metrics are inferred through molecular weight cutoff and positron annihilation spectroscopy. Meanwhile, membrane fabrication involves casting of porous polysulfone onto polyester non-woven fabric, interfacial polymerization (e.g., dipping in m-phenylenediamine aqueous solution), which was later allowed to react with trimesoyl chloride in hexane, and post-treatment involving solvent extraction, thermal curing, and roll storage. Finished membranes are assembled into spiral-wound modules with feed spacers. Feed flows tangentially and permeates the traverse PA-PSU-polyester layers into the permeate channels, while rejected solutes concentrate in the brine stream.

2.4.3. Comparison Criteria of Three Households' Water Treatment Systems: HSF, BSF, and BSZ-SICG

Tables 1 and 2 provide a comparative analysis of household water treatment systems, which are HSF, BSF, and Bio-Sand Zeolite-Silver Impregnated Granular Clay (BSZ-SICG) filters, to evaluate construction for the use of locally sourced materials, contaminant detection using standardized methods, water quality instrumentation, and operational parameters like temperature ranges, flow rates, and daily capacity. These household water treatment systems demonstrate distinct advantages in resource-limited settings. While designs leverage regionally available materials, performance varies significantly with temperature, feed quality, and maintenance. Furthermore, from **Tables 1** and **2**, BSZ-SICG performs well for turbidity, and this is due to its unique multi-layered filter media composition. However, BSZ-SICG lacks cold-climate validation since it relies on a biological layer (*schmutzdecke*) for pathogen removal, in which the cold climates slow microbial activity and reduce bacterial inactivation efficiency. Still, BSZ-SICG is highly effective but complex and expensive, making it suitable for well-supported programs in temperate regions with high turbidity.

2.4.4. Comparison of RBF, SSF, and household water treatment systems

Quantitative sustainability assessments highlight that decentralized filtration systems differ significantly in energy demand, material recyclability, and life cycle impacts. Riverbank filtration (RBF) systems generally exhibit low operational energy use (<0.1 kWh/m³ treated), since they rely on natural subsurface processes; however, land and infrastructure requirements limit scalability in densely populated areas [120]. Further, SSF has demonstrated life cycle greenhouse gas emissions of ~0.05 – 0.1 kg CO_2-eq/m^3 treated water, considerably lower than conventional chemical-based treatments [121]. Furthermore, HSF shows high material sustainability due to the use of sand and gravel, whereas cement-based units are less recyclable and have embodied CO_2 emissions of ~150–200 kg CO_2-eq per unit [122]. In contrast, novel BSZ-SICG filters offer enhanced microbial removal ability, yet raise concerns about silver nanoparticle leaching and limited recyclability of impregnated media [123]. Moreover, energy demand across household filters remains negligible (<0.01 kWh/m^3), which strengthens their case for off-grid communities. Therefore, a comprehensive sustainability perspective must weigh not only contaminant removal efficiencies but also embodied energy, recyclability of materials, and end-of-life impacts to guide technology adoption in resource-limited regions.

While technologies such as riverbank filtration, slow sand filtration, and household bio-based filters demonstrate promising efficiency, their large-scale implementation in developing regions faces significant barriers [49]. Cultural acceptance remains a critical factor, as households may perceive alternative filter media (e.g., bio-sand or zeolite/ silver/clay composites) as less safe compared to commercially packaged solutions, which can limit their adoption despite their proven efficacy [124]. Challenges related to the maintenance of filters also hinder their sustainability, since filters require routine cleaning, replacement of media, and user training, which are often overlooked in low-resource communities [125]. For instance, bio-sand filters may lose effectiveness without proper scouring of the biological layer, and silver-impregnated filters require monitoring of silver leaching to ensure safety [126]. Further, policy gaps exacerbate these limitations, as several developing countries lack standardized guidelines, certification mechanisms, or subsidies to support decentralized filtration systems [127]. Scaling up of these techniques, without supportive regulatory frameworks, remains dependent on non-governmental organizations (NGOs) or donor projects, which eventually restricts their long-term impact [128]. Therefore, addressing socio-cultural perceptions, enabling user-friendly maintenance protocols, and integrating supportive policies are as crucial as technical efficiency for ensuring sustainable adoption of filtration technologies.

3. Conclusion and Recommendation

This review presents a critical and comparative evaluation of various household water filtration systems relevant to developing countries, with a particular focus on their technical performance, adaptability, and sustainability in low-resource settings. The analysis demonstrates that while locally fabricated filters such as household sand filters (HSF), bio-sand filters (BSF), and BSZ-SICG systems show considerable promise in improving water quality and reducing disease burden, each method presents unique limitations. Temperature sensitivity, limited virus removal efficiency, and inability to address dissolved contaminants remain significant challenges across all systems. Notably, social factors such as cultural acceptance and user familiarity often outweigh technical performance in determining real-world adoption and long-term use. Further, enhancing filter media with plant biomass or mineral additives and modifying system components, such as replacing stainless steel with iron-oxide gravel, may improve affordability and chemical stability.

Moreover, this review highlights several research gaps that need to be addressed to strengthen water filtration practices in developing regions. First, there is a lack of long-term field studies under diverse environmental conditions, which limits understanding of filter durability and real-world performance. Second, while conventional and emerging systems show promise for microbial removal, the treatment of chemical contaminants such as arsenic, fluoride, and other persistent pollutants remains underexplored in low-cost applications. Third, the absence of standardized and comparable testing protocols makes it difficult to evaluate and compare results across studies. Future research should therefore focus on large-scale, longitudinal trials, systematic evaluation of both microbial and chemical contaminant removal, and the development of harmonized testing frameworks. Additionally, more studies are needed on user practices, cultural acceptance, and socio-economic impacts to ensure that proposed technologies are not only technically effective but also socially sustainable and scalable in resource-limited contexts. Future progress will require standardized testing protocols under varied environmental conditions (e.g., EPA 1603 methods), as well as affordable innovations in filter media and system design. Overall, this review highlights that while no single filtration method is universally optimal, context-specific design, community engagement, and affordable innovation are key to advancing household water security in developing regions. Hence, future studies should investigate how the water filtration methods can be applied and adapted across diverse contexts in Asia, Africa, and South America.

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Conflicts of Interest

The authors declare no conflict of interest.

Table 1. Comparison of household water treatment systems

Comparison Criteria	HSF	BSF	BSZ-SICG
Construction	Concrete tank, gravel (5-20 mm), sand (0.15-0.35 mm), galvanized iron outlet	Coniferous Pinus bark biomass (CPBB) layer (5-10 cm)	25L buckets, zeolite-clay composite, silver-coated gravel
***E. coli*/*Coliform* Detection**	Oxfam DelAgua field kit (WHO-approved)	Membrane filtration (EPA 1603)	Chromocult agar (ISO 9308-1)
Turbidity Testing	Hach 2100P (0-1000 NTU range)	YSI ProDSS (FNU units)	Hach 2100P (NTU)
pH Measurement	Hanna HI98129 (ATC probe)	Same as HSF	Same as HSF
Hardness/Chloride Analysis	Titration (EPA 130.2)	Ion chromatography (absent in original)	Not applicable
Operating Temp. (°C)	1-25	1-15 (field-tested)	25 (lab-controlled)
Daily Water Input (L)	20	20	25
Flow Rate	0.4-0.6 L/min (unsaturated)	0.36-0.45 L/min (declines over time)	27.5-38.6 L/h
Biomass Media	None	CPBB (enhances adsorption)	None

Table 2. Comparison of household sand filter (HSF), bio-sand filter (BSF), bio-sand zeolite silver impregnated granular clay (BSZ-SICG), and SIPP filters.

Filter Type	Advantages	Limitations	Evidence Source
HSF	- 90-95% *E. coli* removal after maturation - >95% turbidity reduction - 10-year lifespan with scraped maintenance - Material cost: <$15	- Zero dissolved contaminant removal (arsenic/fluoride) - 30-50% efficiency drop at <5°C - Weekly scraping required - No residual disinfection	[129, 130]
BSF (w/ CPBB)	- 97% pathogen removal in Pakistan trials - 50% lower flow decay vs. standard BSF - 40% weight reduction for mountainous use - Adsorbs heavy metals	- <1-log virus removal - Clogs at >50 NTU - 20-30 days maturation period - CPBB replacement annually	[131, 132]
BSZ-SICG	- *E. coli* removal in SIPP configuration - Turbidity: 168 to 0.85 NTU - Zero detectable silver leaching - Reduces diarrheal incidence by 45%	- Antimicrobial failure at Ag<0.1 ppm - Quarterly media replacement - No cold-climate data - High clay sourcing costs	[133-135]

Nomenclature

Al	Aluminium
As	Arsenic
BSF	Bio sand filter
BSZ	Bio-sand zeolite
BOD	Biochemical Oxygen Demand
HSF	Household sand filter
Ce	Cerium
Cd	Cadmium
Co	Cobalt
COD	Chemical Oxygen Demand
CPBB	Coniferous Pinus bark biomass
Cr	Chromium
Cu	Copper
DBP	Disinfection by-product
DMF	Dimethylformamide
DMSO	Dimethyl Sulfoxide
DOC	Dissolved Organic Carbon
GAC	Granular activated carbon
GDM	Gravity-driven membrane
GO	Graphene oxide
GWUDI	Groundwater under the direct influence of surface water
Hg	Mercury
NGFs	Nano Glass Flakes
HNT	Halloysite nanotube
HPHT	High-pressure high temperature
HSF	Household Sand Filters
ICP-MS	Inductively coupled plasma mass spectrometry
IESWTR	Interim Enhanced Surface Water Treatment Rule
KAP	Knowledge, Attitude, and Practices
La	Lanthanum
LT2ESWTR	Long Term 2 Enhanced Surface Water Treatment Regulation
MPD	m-phenylenediamine
MWCO	Molecular weight cutoff
NF	Nanofiltration
NGFs	Nano Glass Flakes
NOM	Natural organic matter
NTU	Nephelometric turbidity units
PA	Polyamide
PAN	Polyacrylonitrile
PAN/HNT	Polyacrylonitrile/halloysite nanotube
Pb	Lead
PSU	Polysulfone
PWSs	Public water systems
Rb	Rubidium

RBF	Riverbank filtration
RBFW	Riverbank filtration well
REE	Rare earth elements
RO	Reverse osmosis
Sc	Scandium
SDWA	Safe Drinking Water Act
SIPP	Silver-Impregnated Porous Pot
SS	Suspended solids
SSF	Slow sand filtration
SWTR	Surface Water Treatment Rule
Th	Thorium
TMC	Trimesoyl chloride
UASB	Anaerobic up-flow sludge blanket
UF	Ultrafiltration
UNICEF	United Nations Children's Fund
US	United States
WHO	World Health Organization
Zn	Zinc
SICG	Silver impregnated granular clay

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