Review

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Abstract: Providing safe drinking water to people in developing countries is an urgent world-wide water problem and a main issue in the UN Sustainability Goals. One of the most efficient and cheapest methods to attain these goals is the use of slow sand filters. Slow sand filters can efficiently provide safe drinking water to people living in small rural communities not served by central water supply systems. The purpose of this review article is to critically summarize and synthesize features and advantages of slow sand filtration methods to improve the quality of drinking water with special focus on less-developed countries. Even though slow sand filtration is an old technique, its efficiency and cost-effectiveness make it important to continue to develop the method in parallel to other chemical and biological methods. Thus, there are needs to continue to develop methods for slow sand filtration combined with simple disinfection techniques for treatment of microbiological pollutants such as bacteria, microbes, viruses, and parasites. These techniques can be applied before or after the sand filter application. Studies are also needed to investigate other types of porous material in areas where suitable sand and gravel are not readily available. Methods are needed to reduce the contents of emerging environmental pollutants such as surfactants and microplastics. Also, further studies are needed to determine design criteria (particle size distribution, depth of media, residence time, temperature, etc.) for different types of pollutants, existing and emerging. Finally, further research is needed to advise on life cycle time, operation (e.g., batch or continuous flow), and maintenance procedures (cleaning of media, back-flushing, etc.) for used porous media in slow the sand filtration.

Keywords: slow sand filtration; developing countries: microbes; parasites; turbidity; safe drinking water; water treatment

1. Introduction

Currently, the issue of providing the population with quality drinking water is one of the most acute problems in the world. Only 2% of Earth's water are fresh and the problem of providing safe drinking water to the global population in view of climate change is getting worse. In addition, the rapid development of industry and emerging pollutants increase the risk of water pollution by substances harmful to human health. More than 1 billion people do not have access to safe drinking water, 80% of them live in rural areas, and up to 6 million people die each year from illnesses caused by contaminated water [1–4]. The greatest risk associated with ingestion is harmful microbial infection risk due to human and/or animal fecal contamination. Consumption and infection from contaminated water in developing countries cause thousands of deaths every day, mostly affecting children under the age of five [2]. According to the World Health Organization [3], the leading causes of death among children worldwide, after respiratory disease, are drinking contaminated water and poor hygiene. In 2012, more than half a million deaths in low- and middle-income countries were due to drinking poor-quality water [4]. Water, sanitation, and hygiene (WASH) problems cause stunted children and great economic losses in the developing world.

In view of the above, slow sand filtration (SSF) has historically been one of the most important methods to treat water for drinking and eradicate WASH problems. Due to its efficiency and low cost, SSF is still considered an effective and inexpensive way to provide clean drinking water in less-developed countries with limited water resources. SSF is recognized by the U.S. Environmental Protection Agency (USEPA) and WHO as an inexpensive and reliable way to improve safe drinking water [5,6]. Therefore, this method is still used in rural areas and even in some larger cities of the world to provide the population with good quality drinking water [7]. Characteristic features of the SSF are simple construction, low energy consumption, low filtration rate, no chemical pre-treatment of water, and cleaning of filtering layers by scraping the surface or sand removal [8]. However, surprisingly only about half a million people in developing countries at present use SSF for drinking purposes [7]. In view of this, the objective of this review article is to critically summarize and synthesize features and advantages of SSF methods for less-developed countries to improve the quality of drinking water. After giving a brief introduction to present main raw water purification methods, SSF is summarized and assessed. We close with a reflection on research needs to further improve the SSF methods with application to less-developed countries.

2. Contemporary Raw Water Purification Methods

To date, there are various methods of treatment of raw water for drinking purposes. Which treatment method to be used to treat the water depends on its chemical composition, turbidity and size of particles (impurities) present and, purpose of use and distribution system to end users. The following contemporary methods to treat raw water are presently often used.

2.1. Mechanical filtration

Mechanical filtration is considered the simplest among the known methods of water purification. This method is usually used to purify water from turbidity and various insoluble substances. For this purpose, the water to be treated is passed through a porous medium constituting a filter. Various solids and filters (sand, gravel, clays, zeolites, bentonites, activated carbon, etc.) are used as a permeable porous medium [9–11]. The size of the detained (not passing through the filter) particles must be larger than the diameter of "holes" between the filtering particles. According to calculations, if diameter of homogeneous spherical filter particles is equal to d, then particles with diameter more than $0.15 \times d$ do not pass through the filter pores. And when passing water through the column filled with powdered activated carbon with particle size of 0.1-1 mm, particles of about the same size are detained.

However, with mechanical filtration it is often difficult to purify water from microorganisms, bacteria, and viruses, as the size of these ranges from 0.005 to 3 microns that easily pass through the filter. The mechanical filtration method is usually used for pre-treatment of water taken from open water bodies (rivers, lakes, reservoirs) from relatively large particles of pollutants. In mechanical filtration the treated water usually passes through the filter by gravity [12].

2.2. Reverse osmosis

In this method water is purified from unwanted impurities with the help of a reverse osmosis membrane by passing water through the membrane under pressure. The water passes freely through the membrane while other substances present in the water are retained [13]. Using this method water can be purified from various (even from monovalent) ions and obtain water of high quality (by composition close to distilled water). However, this method has several drawbacks [14,15]. First, this method has low selectivity, i.e., all "useful" and "harmful" substances for the human body are retained during water purification by the membrane. Therefore, to use water purified by this method as drinking water, it will be necessary to repeatedly add salts needed for the body. Secondly, the cost of

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reverse osmosis units is relatively high, and the productivity of the process is usually rather low (20-30 L/day). Thirdly, before using reverse osmosis, the water must be cleaned of relatively large mechanical impurities by filtration. Because large particles clog the pores of the membrane, as a result, the performance of the process drops, and the service life of the installation is dramatically reduced.

2.3. Ion exchange

The purification of contaminated water by this method is based on the ion-exchange process occurring between water and the sorbent (ion-exchange resin) [16,17]. The ion exchange method can selectively purify water from ions. For this purpose, the raw water is passed through the sorbent (ion exchanger). In this case, the ions present in the water are adsorbed on the surface of the sorbent, and the water from the ion-exchange resins is transferred to an equivalent number of ions with the same charge with respect to the adsorbed ions. For example, the ion exchange process is often used to eliminate water hardness (to reduce the concentration of Mg^{2+} and Ca^{2+}). For this purpose, ion exchangers (cation exchangers) containing a harmless cation (e.g., Na^{+}) are used. When hard water is passed through the cation exchange resin, an ion exchange process occurs between the water and the ion exchange resin, because of which the calcium and magnesium cations present in the water are adsorbed on the surface of the cation exchange resin, and sodium cations from the ion exchange resin are transferred to the water. The ion exchange process is often used to remove heavy metal cations from water and to extract various ions from industrially polluted water [18–20]. The efficiency of the ion-exchange process for water treatment largely depends on the exchange capacity of the sorbent, i.e., the ability of the sorbent to adsorb a certain amount of ions from the solution composition, and on the cost of regeneration of the spent sorbent.

2.4. Electrochemical purification

Electrochemical treatment is based on passing a strong electric current through the water to be treated [21,22]. When an electric current is applied, substances in the water participate in redox reactions (electrolysis), because of which they are transformed into other "harmless" substances. The electrochemical method is more efficient in terms of economy and its performance is very high. With this method it is possible to purify water from almost all microorganisms and obtain high quality water [23]. However, if the water contains various organic substances, under the influence of a strong current, they can undergo complex changes, resulting in the formation of harmful substances to the environment. Therefore, before using this method, it is necessary to know in advance what substances the impurities present in the composition of water can be transformed into during electrolysis.

2.5. Distillation

The distillation method is based on the conversion of water to steam by heating the solution and then condensing the water vapor [24,25]. With this method water can be cleaned from dissolved solid impurities, resulting in chemically pure (distilled) water. However, this method is expensive and the components (salts) necessary for human organism should be added to the distilled water to be used as drinking water. The main disadvantage of this method is the inability to purify water from low volatile organic substances by distillation. Therefore, to remove volatile organic compounds, the water is usually first passed through an adsorbent (e.g., activated carbon).

2.6. Sorption

Sorption refers to the adsorption by solid particles of components of gas mixtures and liquid solutions [26–28]. In this method, for the purpose of treatment, contaminated water is passed through a vessel filled with sorbent medium. The impurities in the water are adsorbed on the surface of the sorbent particles and the purified water flows out from the bottom of the sorbent. In this method the degree of water purification depends on many factors: size of the particles (specific surface area) of

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the adsorbent, nature of the interaction of components present in the water with the adsorbent surface, pressure, and temperature. With decreasing particle size (with increasing specific surface area) sorption capacity of a solid increases dramatically. Various substances can be used as adsorbents [29,30]. To date, the most common (widely used) sorbent for water treatment is activated carbon. By activation the specific surface area of carbon can be increased up to 1000-1500 m^2/g. Activated carbon can be used to purify water from substances of different chemical nature. Therefore, activated carbon is one of the main sorbents used in many commercial filtration plants today.

2.7. Coagulation and flocculation

Coagulation and flocculation are processes of precipitation of suspended dispersed particles present in solutions by adding electrolytes (coagulants) and water-soluble polymers (flocculants) [31–34]. They can be used to concentrate impurities in a flocculent form, which can be easily removed by sedimentation. Introduction of coagulants into suspension leads to reduction of electrostatic repulsion force of disperse particles due to neutralization of surface charges and reduction of electro-kinetic (zeta) potential of particles. Flocculation is a form of coagulation, when fine suspended disperse particles in a liquid or gaseous medium, form loose flocculated clusters, i.e., floccules. Natural [35,36] and synthetic water-soluble polymers [37,38] and their polycomplexes [39,40] are used as flocculants for raw water treatment.

3. Slow Sand Filtration

3.1. History

Filtration methods are traditional techniques of water purification used by mankind since ancient times. By filtering, water can be cleaned of sand, silt, turbidity, scale, and other suspended particles. According to [41], people used sand and gravel filters as early as 2000 BC in ancient India. In ancient times, the Romans built canals near lakes to take advantage of natural filtration through the canal walls.

Modern slow sand filters (SSF) for water purification were first used in the 19th century in England. Therefore, they are often called English filters. The first slow filter was built by the English engineer James Simpson in 1829 in London to purify water from the river Thames [42,43]. But various designs of sand filters were used for water purification in earlier years in several Scottish cities: Paisley (1804), Glasgow (1807), and Greenock (1827) [44,45]. In Berlin slow filters were built in 1853, in Warsaw in 1880, and in Moscow in 1902 [46]. In the United States the first SSFs were built in 1872 at Poughkeepsie, New York [47,48], which operated until 1959 [49]. Thus, slow filtration of water has been an effective way to prevent the spread of various gastrointestinal diseases through drinking water for over 150 years [51]. In 1855 John Snow, in his essay "On the Means of Transmitting Cholera," suggested a correlation between the spread of the cholera epidemic and the quality of the water supply in Soho [52]. According to Wegelin [53], "no other simple purification process can improve the physical, chemical, and bacteriological quality of surface waters better than SSF." In 19th century Europe, SSF of water was recommended as one of the effective ways to prevent the spread of an infectious disease, the cholera epidemic [54]. SSF can eliminate 90-99% of bacteria and viruses, remove 93.3% of fecal coliforms, and completely remove Giardia lamblia cysts and Cryptosporidium oocysts [55]. In view of its efficiency for basic raw water treatment and low-cost characteristics, it is noteworthy that only about half a million people in developing countries use SSFs obtain a basic quality drinking water [7,50]. Obviously, SSF has a much larger role to play in this regard to help reaching the UN Developing Goals.

3.2. SSF requirements

A distinction can be made between rapid sand filtration and SSF of water [56–58]. SSFs have an effective particle size diameter of 0.15-0.35 mm and a uniformity factor of 1.5-3.0. The effective particle size for trapping in fast filters is greater than 0.55 mm with a uniformity factor of less than 1.5. The water filtration rate in fast filters varies between 4-21 m/h (100-475 $m^3 \times m^{-2} \times d^{-1}$) [59] and in

SSF varies from 0.1 to 0.4 m/h (1-8 $m^3 \times m^{-2} \times d^{-1}$) [60]. The difference between these two methods is not only in the filtration rate, but most importantly, in the technology of water purification. Table 1 provides a list of particles frequently present in raw water [61].

Table 1. Examples of elements found in raw water [61].

Category	Group/Name	Size (µm)
Mineral	Clays (colloidal)	0.001–1
	Silicates	No data
	Non-Silicates	No data
Biological	Virus	0.001–0.1
	Bacteria	0.3–10
	Algae, unicellular	30–50
	Giardia cysts	10
	Parasite eggs	10–50
	Nematode eggs	10
	Cryptosporidium oocysts	4–5
Other particles	Amorphous debris, small	1–5
	Organic colloids	No data

SSF refers to biological water treatment methods, although in this case there is also a physical (inertial collision and attachment, diffusion, adsorption, and sedimentation) separation of dispersed particles [61]. Fast sand filtration is a purely physical method of water treatment. SSF is an effective way to remove microbial contaminants and bacteria as well [62,63]. Particles are mainly removed in the upper part of the sand layer [64]. Nonpathogenic aerobic microorganisms deposited on the surface of the sand filter can metabolize organic matter that enters the filter with the incoming water. These microorganisms can prey on bacteria and viruses present in the water [65].

SSFs represent many advantages over other water treatment methods. They do not require chemical reagents and qualified specialists, are easy to operate, have minimal maintenance and manpower requirements, low capital and operating costs and low energy requirements [66–68]. For this reason, SSF has found widespread use in rural areas to provide good quality drinking water [69]. However, there are some limitations, e.g., SSF is not recommended for water treatment with turbidity greater than 5 nephelometric turbidity units (NTU), because high turbidity can lead to filter clogging and thereby shorten the life of the filter [70]. Apart from turbidity, for successful application of SSF treatment, chlorophyll content in feed water must be <0.05 µg/L; iron and manganese must not exceed 0.3 and 0.05 mg/L, respectively. The quantity of dissolved heavy metals, pesticides, and colorants must be minimal and presence of residual oxidant before filtration is not desired [70]. At the same time, SSFs are better at purifying water contaminated with non-clayey impurities [71].

In Saskatchewan, Canada [72], a modular SSF polyethylene system was developed and tested that incorporated pretreatment and post-treatment processes such as ozone oxidation, pretreatment, and biological activated carbon (BAC) filters to provide significant reduction in turbidity, heavy metals, color, and organics. In the initial period, the filtration efficiency without the Schmutzdecke layer may not be more than 60% [73]. Several studies [74,75] summarizes work on the modification of SSFs, which help to eliminate the limitations of the application of this method.

Currently, for the preparation of potable water in many cases, chemical methods of treatment are used. However, the use of reagent methods at small treatment plants may create problems associated with the lack of qualified specialists, with the high cost of equipment and chemical reagents used for water treatment. This fact leads to the conclusion that reagent-free water treatment methods often are better suited for rural areas in developing countries.

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3.3. SSF biological processes

There are two important mechanisms regarding the filtration of particles and microorganisms through a slow sand layer: the transport mechanism and the attachment mechanism [75]. According to the transport mechanism, particles in water that are larger than the pore diameter of the sand layer cannot pass through the filter and are retained on the surface of the sand layer. Larger particles are mainly retained by the transport mechanism. However, as the particles settle and the biofilm "matures" on the surface of the sand layer, the pore diameter of the sand filter gradually decreases. Because of this, particles, and microorganisms much smaller than the pore diameter of the sand bed can be retained on the surface of the sand bed [76]. The particles (microorganisms) present in the water adhere to the sand layer surface through Van der Waals or electrostatic forces of attraction [77–80]. In this case, formation of chemical (e.g., hydrogen) bonds between particles and solid surface cannot be excluded as well. Bacteria (size 0.01-10 µm) [81], viruses (0.01-0.1 µm) [82,83], and colloidal particles (0.001-1 µm) [77] are mainly retained by this mechanism.

3.4. General construction of SSF

Traditional slow filters are usually tanks up to 6 m wide, up to 60 m long and consisting of four layers (Figure 1) [65,75,80]. Drainage is placed on the bottom of the tank. Hollow pipes, bricks, or concrete slabs with gaps are usually used as drainage. A supporting layer (approximate thickness of 0.5 m) of gravel, pebbles or crushed stone is placed on the surface of the drainage. The particle size of the supporting layer can vary from 2 to 30 mm. Above the supporting layer a filtering layer of sand (thickness 450-1250 mm) is placed with a developed surface and high porosity. The sand particle size can vary from 0.2 to 2 mm [84,85]. On the surface of the filtration layer the supernatant water is located. The supernatant layer must provide the necessary head to filter water through the porous sand layer [8]. The flow rate can be regulated by changing the difference between the head of the supernatant water and the height at which the discharge pipe is open to the atmosphere.

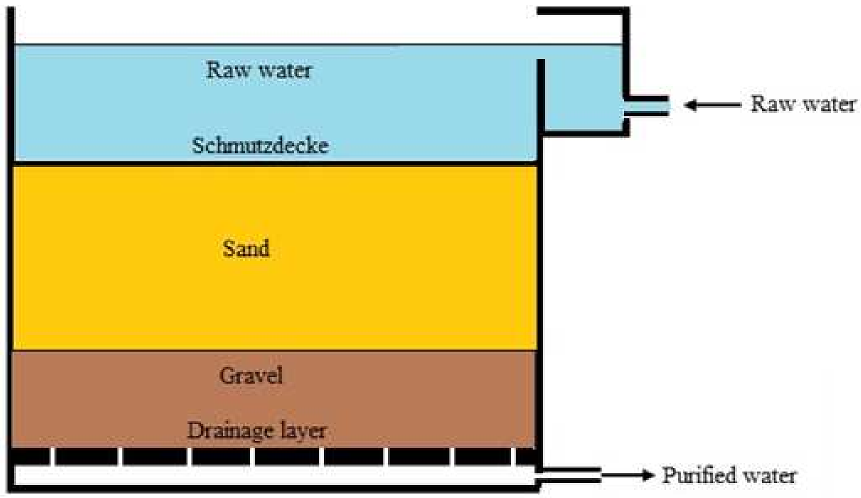

Figure 1. Schematic of a general SSF design.

It is regarded [80] that a sand layer thickness of 0.3 m is sufficient for proper removal of turbidity and coliform bacteria, and a thickness of 0.6 m for significant removal of virus from the water composition. Changing the thickness of the sand layer affects the removal rates of bacteria and viruses. For example, a decrease in sand layer thickness from 0.6 m to 0.3 m resulted in a 0.04% decrease in poliovirus (poliovirus) removal (from 99.98% to 99.94%) [65,86], and a 2% decrease in coliform removal (from 97% to 95%) observed when filter layer thickness was reduced from 0.97 m to 0.48 m [61,87].

Depending on the weather conditions, the slow-filter tank can be located outdoors or indoors. During the cold winter period it is recommended to conduct the filtration process indoors, especially at subzero temperatures. Over time, as the biofilm thickens, the SSFs gradually lose their efficiency and the flow rate through the filter decreases. In this case, it is necessary to rebuild the filter. As a rule, the duration of an SSF is from 30 to 60 days, but sometimes it can reach more than 100 days [75,80].

3.5. Slow sand filter regeneration

There are two main methods of filter layer regeneration: 1) with removal of the upper contaminated layer of sand and 2) with washing of the contaminated sand surface layer directly in the filter by mechanical or hydraulic loosening and removal of contaminants by a stream of clean water (wet harrowing) [88,89]. In the first method, the top layer of sand is periodically (2-3 times a month) removed and washed several times with clean water. After that, the cleaned sand is loaded back into the tank.

3.6. SSF speed mode

The slow filtration rate depends on the suspended solids content of the raw water. At a particle concentration not more than 25 mg/L the filtration speed is 0.08-0.4 m/h [90], and at a particle concentration exceeding 25 mg/L the filtration speed varies from 0.1 to 0.2 m/h.

Contaminated water in slow filters is purified with the help of a "biological film" that forms on the surface of the filtering sand layer from algae, bacteria, and settled contaminant particles. Such a film is called the hypogeal layer or the Schmutzdecke (German for "dirt layer") [61,76,91–94]. The duration of filter maturation significantly affects the rate and degree of removal of microbial and organic contaminants by the filter [7,86]. An effective biological film forms during the first 10-40 days of the SSF process of water [7,95–97] and provides detention of up to 90-98% of highly dispersed solids, bacteria [98], reduction of fecal coliform bacteria, and turbidity per log10 [96], reduction of total coliforms and turbidity to 97% [99]. A low filtration rate is necessary for complete biological processes in the filter [100,101].

SSF can remove pathogenic microorganisms, suspended organic and inorganic contaminants [84,102], turbidity [102], bacteria, virus, and enteroparasite cysts [86,102,103,]. Meanwhile, the main biological mechanisms responsible for the removal of bacteria in slow sand filters are predation by algae, eating detritus by aquatic worms, natural mortality, inactivation, metabolic breakdown, and adsorption on the sticky zoogleal surface of the sand [92,102–104].

The sorption capacity of the Schmutzdecke layer is estimated through the sorption coefficient (K_d), which is calculated using [105]:

$$K_d = \frac{C_s}{C_e} \quad (1)$$

where C_s is the milligram of sorbed antimicrobial per kilogram of solid, mg/kg; C_e is the aqueous antimicrobial concentration mg/L after 24 h equilibration. Sorption coefficients are normalized to the share of organic ($K_{oc} = K_d/f_{oc}$) and organic matter ($K_{om} = K_d/f_{om}$) where f_{oc} and f_{om} are mass fraction of organic carbon and organic matter in the Schmutzdecke layer, respectively.

3.7. Influence of various factors on SSF

The size and homogeneity of sand particles essentially influence the efficiency of water purification with a SSF [106]. The homogeneity of the particles is determined by the homogeneity coefficient. The homogeneity coefficient of sand is defined as the ratio: coarseness at which 60% (by weight) of the sand sample pass through the sieve divided by the coarseness at which 10% of the same sample (by weight) pass through the sieve, i.e., $K_{60/10} = d_{60}/d_{10}$. A uniformity factor of 1 means that all particles are the same size. As the uniformity of the sand particles increases, the filtration efficiency increases. If the sand particles vary greatly in size, the smaller sand particles will fill the gaps between the larger particles, resulting in filter clogging [107]. The most effective sand particle size for slow filtration is 0.15-0.35 mm and a uniformity factor of less than 2 [108].

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The thickness of the sand layer has a significant influence on the degree of removal of contaminants from the water composition by the method of SSF. It is generally assumed that the thicker the sand layer, the greater the retention of fine and colloidal particles, viruses, and the better the discoloration of water. According to [109], a sand layer 200 mm thick removes 99.5% of fecal bacteria. The minimum thickness of the sand layer to remove turbidity and coliform bacteria is 300 mm, while 600 mm sand thickness is sufficient to remove all viruses [80].

According to [65], the key design parameter of SSF controlling water quality is the filter's hydraulic residence time (*HRT*). *HRT* is determined by:

$$HRT = V \times n/Q \quad (2)$$

where Q is the water volume flow rate, m^3/h; V is the total sand volume, m^3 and n is the sand porosity. The porosity of sand usually ranges from 0.35 to 0.50. This means that 35 to 50% of the volume of the active filter is water in contact with microorganisms attached to the sand grains. Reducing the sand particle size increases the water-sand contact surface area and the porosity of the material. On the other hand, a wide range of particle sizes reduces the porosity of the sand layer, which leads to lower *HRT*. Therefore, the sand must have a sufficiently high homogeneity. According to [65], the use of a sand layer consisting of particles with a size of 0.35-1.5 mm provides a high degree of water purification at HRT from 8 to 12 hours.

3.8. Purification of water from ions, bacteria, and microbes

SSF can also be used to purify water from ions. However, there are chemical impurities that cannot be effectively removed by SSF alone. These include sulfate (SO_4^{2-}), nitrate (NO^{3-}), sodium (Na^+), calcium (Ca^{2+}), magnesium (Mg^{2+}) ions and water hardness (as $CaCO_3$) [110,111]. According to [110], biological treatment converts most ammonium ions (NH_4^+) to nitrate ions (NO_3^-). In addition, stable colloidal particles are also difficult to remove by SSF [71,72].

In the last two decades, so-called bio-sand filters (BSFs) have become widespread. For example, the company CAWST (Center for Accessible Water Supply and Sanitation Technology) in Calgary, Canada, has developed concrete filters made of bio-sand, which are used in 450 organizations in more than 55 countries [73,74]. Triple Quest of Grand Rapids, USA, offers bio-sand filters 60 L HydrAid filters made of plastic [65,112,113]. Plastic biosand filters are relatively cheap and lighter than concrete BSFs [114]. The authors [65] proposed a modified household plastic filter (BSF). In the new filter design the gravel layer is replaced by a thin porous plastic plate placed in a plastic bag. This replacement reduces the required filter media and increases the total pore volume in the core. As a result, the cost and labor required to install and maintain the filter is reduced.

A study [115] proposed a household SSF for removal of As, Fe, and Mn from the composition of groundwater for rural areas in Vietnam. The sand for filtration was collected from the banks of the Red River. It was found that nitrate-reducing Fe(II)-oxidizing and Fe(III)-reducing bacteria were present in the dry sand, while microaerophilic Fe(II)-oxidizing bacteria were absent. And, Mn-oxidizing bacteria were found in the composition of the dry sand. Based on the analysis of the composition of the microbial community, the authors concluded that the abiotic processes of oxidation of Fe(II) prevail over the biotic oxidation of Fe(II) on the filter. Moreover, Mn-oxidizing bacteria played an important role in Mn(II) oxidation and deposition of Mn(III/IV) oxide in a separate layer of the sand filter. The formation of Mn(III/IV) oxides promoted abiotic oxidation of As(III) and immobilization of As(V) by sorption onto (oxy-hydro) oxides of Fe(III). This resulted in a significant reduction of As, Fe, and Mn concentrations in filtered groundwater.

In several studies [116–118] the design and principle of operation of a slow self-cleaning filter for natural water deferrization were proposed. A Birm Regular filter was used as a filter load, which simultaneously acts as a catalyst for the reaction of oxidation of Fe^{2+} by oxygen to Fe^{3+}. Trivalent iron cations are hydrolyzed to $Fe(OH)_3$ and then positively charged colloidal particles of Fe(III) hydroxide are formed [119]. Positively charged colloidal particles of iron (III) hydroxide are adsorbed on the negatively charged surface of the particles of filter media, resulting in the formation of a dense gel-like adsorption layer on the surface. Such a layer is an effective filtering material. The concentration

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of $Fe(OH)_2$ varied from 6.0 to 16 mg/L in the model natural water (simulant). It was established that the output of the filter to the working mode at Fe^{3+} concentration in the model solution of 16.0 mg/l was not more than 2.0 hours. The analysis of the experimental data obtained for water with iron concentration of 16.0 mg/L has shown that at the first stage of filter operation the Fe^{3+} concentration in the treated water decreases from 16.0 to 0.9 mg/L after 20 min of filtration and after 1.5 hr it was 0.1 mg/L. The maximum allowable concentration for Fe^{3+} in drinking water is 0.3 mg/L [120]. According to the authors, the use of the proposed design for pre-treatment of water from iron ions, will significantly reduce the load on the stage of the final purification of water from iron.

In [121] the possibility of removing cyanobacterial hepatotoxins (microcystins) from the composition of water taken from Berlin lakes using SSFs was studied. Two full-scale experiments were performed: one experiment was performed with dissolved microcystins extracted from a cyanobacterial flower in one of the Berlin lakes. The second experiment was performed with a longer exposure of live cyanobacterial cells (collected from the same lake) to the filter. It was found that the experiment with dissolved microcystins revealed high rates of microcystin elimination (95%) within the sand filter bed and with a half-life for microcystins of about 1 hr. In the second experiment, where cell-bound microcystins were used, rather good results (elimination of 85%) were also obtained in the first days after application of cyanobacteria. However, as the temperature decreased to 4°C, elimination decreased to 60%, which, according to the authors, is associated with a slowing down of bacterial biodegradation at low temperature. Thus, it was concluded that at moderate plus temperatures, slow filtration through sand can serve as an effective method of removing microcystins from drinking water composition.

In [105] the efficiency of removal of water-soluble antimicrobials such as sulfamethazine (SMZ), tylosin (TYL), sulfamethoxazole (SMX), trimethoprim (TRI) and lincomycin (LIN) from water in rural areas by SSF was studied. Basalt sand was used as filtering material. Water-soluble antimicrobials are used in livestock and poultry production to promote growth and prevent bacterial infections. In rural areas, surface water may be contaminated by antimicrobials from wastewater or by diffuse contamination from the application of manure and processed biological solids containing antimicrobial residues to the soil [122–124]. Experiments were carried out using coarse (fast) and SSF methods. The coarse filter showed low antimicrobial removal efficiency. SSF showed effectiveness in removing antimicrobials, with the sorption of drugs on the surface of the filter layer changing as follows: TYL > TRI > LIN > SMX > SMZ. At the end of the 14-day period of the SSF study, the following results were obtained: >99% TRI removal, <25% LIN removal and <4% sulfonamide antimicrobial removal from the contaminated river water.

In [125], slow and fast sand filtration methods were used to remove Triactinomyxon actinospores (Tams) of the salmon parasite Myxobolus cerebralis from contaminated water. Sand with a particle diameter of 0.180 mm was used as filter material. The sand cushion of the filter was 17.8 cm and the support gravel was 17.8 cm. Aquarium fish were used as targets of Tams infestation. Tams were introduced into fish rearing systems over sand filters. The rapid filtration method was tested with two backwashing regimes. In the first, a continuous backwash was performed, and in the second, flow was diverted past the fish tanks for 5 min after backwashing. SSF through a sand filter without backwashing served as a control for the two fast filters. After 60 days, clinical signs of circling behavior and black tails were seen among the positive controls. Polymerase chain reaction (PCR) analysis for Myxobolus cerebralis showed that infections were absent in both fast sand filter water treatments. Whereas 1.6% of all fish were infected with the SSF treatment. Based on these results, the authors concluded that both fast and SSFs can be used to remove Tams from the water composition and the backwash method is important for the reliable functioning of fast sand filters [125].

5. Conclusions

The above review shows that there are ample possibilities for simple, cost-effective, yet effective applications for extended use of slow sand filtration (SSF), especially in rural areas that are difficult to reach by central raw water treatment plants. The efficiency and cost-effectiveness of the SSF make this method especially suited for less-developed countries. Filters are easy to manufacture from local material and do not require expensive additional chemicals or complicated operation and maintenance. The following reflections and conclusions can be made regarding SSF and possibilities to extend its use:

SSF functions rather well as bio-filters that are important for less-developed countries. However, to further continue to develop methods for SSF, combined use with disinfection techniques for further water purification from microbiological pollutants such as bacteria, microbes, viruses, and parasites can be performed. These techniques can be applied before or after the SSF application.

1. Studies are needed to investigate SSF using other types of basic material in areas where suitable sand and gravel are not readily available. This is especially important for less-developed countries and regions where sand or gravel are not readily available.
2. It is becoming especially important, especially for less-developed countries, to test and develop SSF methods to reduce contents of emerging environmental pollutants such as surfactants and microplastics.
3. Further studies are needed to determine design criteria (particle size distribution, depth of media, residence time, temperature, etc.) for different types of pollutants, existing and emerging.
4. Further research is needed to advise on life cycle time, operation (e.g., batch or continuous flow), and maintenance procedures (cleaning of media, backflushing, etc.) for used porous media in SSF.
5. Surprisingly few people in less-developed countries still have not access to SSF to obtain safe drinking water. This is noteworthy in view of the SSF simplicity and efficiency in preventing WASH diseases. Obviously, SSF has a much larger role to play in helping to reach the UN Developing Goals.

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