

Communication

Universal Access to Safe Drinking Water: Escaping the Traps of Non-Frugal Technologies

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Abstract: This communication is motivated by recent publications discussing the affordability of appropriate decentralized solutions for safe drinking water provision in low-income communities. There is a huge contrast between the costs of presented technologies, which vary by a factor of up to 12. For example, for the production of 2000 L/d of treated drinking water, the costs vary between about 1500 and 12,000 Euro. A closer look at the technologies reveals that expensive technologies use imported manufactured components or devices that cannot yet be locally produced. In the battle to achieve the United Nations Sustainable Development Goal for safe drinking water (SDG 6.1), such technologies should be, at best, considered as bridging solutions. For a sustainable self-reliance in safe drinking water supply, do-it-yourself (DIY) systems should be popularized. These DIY technologies include biochar and metallic iron (Fe⁰) based systems. These relevant technologies should then be further improved through internal processes.

Keywords: appropriate technologies; cost-effectiveness; indigenous knowledge; point-of-use systems; self-reliance; water supply

1. Introduction

The international community has achieved the Millennium Development Goal 7C of halving the number of people without access to “improved” water supply by 2015 [1,2]. However, this success still leaves some 1.8 billion world citizens without safe drinking water, and 144 million continue to drink untreated surface water drawn from rivers or lakes [3,4]. It is hoped now, that through a synthesis of available knowledge and concerted research efforts, universal access to safe drinking water will be achieved by 2030 [1,5,6].

The battle for a universal safe drinking water supply had started around 1950, when the world was divided into the following two groups: (i) the developed world with universal access to safe drinking water (and sanitation), and (ii) the developing world without proper access to safe drinking water, and a population prone to waterborne diseases [4,7]. It is rather surprising, that apart from China and a few countries who have significantly progressed since then, the situation remains unchanged 70 years later. This

is certainly a reason to question the past and current approaches to clean drinking water supply. It should be recalled that sound principles for designing affordable systems for safe drinking water supply are documented in many old textbooks [8–10], review articles [11,12], and books on the history of water treatment [7,13]. In particular, the century-old textbook “An Elementary Handbook on Potable Water” [10] by Floyd Davis (1891) is very illustrative. Floyd Davis had already identified filtration using sand, animal charcoal (bone char), and wood charcoal as powerful tools to obtain high quality water for many purposes. However, while sand has been (to some extent) continuously used in water treatment plants [7], bone char has been outscored by other (re)active materials, including granular activated carbon (GAC). Bone char was almost independently re-discovered twice for water defluoridation: (i) during the 1930s as fluoride was established as a severe water pollutant [14,15], and (ii) during the late 1970s to solve the fluoride crisis in the developing world [16,17].

The main weakness of previous and current approaches can be traced to a paternalist way of thinking and doing. This approach regards the whole developing world as a burden for the developed world who has assigned itself the task to develop and transfer technologies to the rest of the world [4,18,19]. The notion of technology transfer and capacity-building as an approach to address problems in low-income countries is prevalent in water and sanitation and even public health, especially in Africa [20]. The fallacy of this approach is inherent to the Western elitist education system [21], and its wide adoption in the developing world [22,23]. In fact, even within the Western World, any knowledge shall be validated by universities. Using this approach, any other knowledge developed outside academia is often considered inferior and relegated to indigenous knowledge (systems), while some are still not validated by the academia. An example of this is rainwater harvesting (RWH), which is the oldest form of water supply ubiquitous to every society [23–25] but is currently perceived as a new or recent technology [26–28].

While there is no problem with validating knowledge by experts, the problem arises when people in their natural environments are declared incompetent and condemned to wait for transferred technologies through capacity-building by external experts [21,26]. Moreover, even when more or less successfully transferred, there has been little capacity building, and the net result has been failure after the first technical problem [18,19,29]. The drinking water sector has not been an exception. In the past few decades, there has been an increasing interest for a participatory approach in introducing and disseminating new water treatment technologies [21,30–32]. This was characterized by terms such as “co-development”, “knowledge democracy”, “cognitive justice”, and has culminated in empowering the people to be self-reliant in water supply [32–37]. In particular, Dr. Josh Kearns at North Carolina State University in the United States of America has developed an adaptable, modular, and transferable do-it-yourself technology—a biochar-based water filtration unit with capacity to produce up to 2000 L/d that can be assembled in Thailand for less than 1500 Euro (www.aqsolutions.org, 25 May 2021). Moreover, this filtration technology addresses both microbial and chemical contamination. In fact, 1500 Euro corresponds more or less to the flight ticket of an expert from Europe to Thailand and is far less than the shipping cost of an expensive device for water treatment that dominates the current technology transfer paradigm [3,38].

This communication seeks to demonstrate that universal self-reliance in safe drinking water provision is possible using locally available materials, including gravel and sand, and the concept of the modular treatment train presented on YouTube by **Aqueous Solutions** (www.aqsolutions.org, 25 May 2021). “**Aqueous Solutions**” is a non-governmental organization (NGO) based in Thailand and in the United States of America (USA). The article presents two “co-development” technologies based on (i) biochar, and (ii) metallic iron (Fe^0). Both technologies have been intentionally developed during the past 15 years as DIY options. Furthermore, it is shown that Fe^0 -based units can be incorporated in the modular treatment train of **Aqueous Solutions**. **The resulting** technologies are discussed for their universal self-reliance application. Clearly, it is not only about the affordability of individual components, but the treatment chain as a whole. Research and development

on such systems remains limited and is often just published as book chapters [37,39,40] or academic dissertations [41–43].

The presentation will start with the methodology used for this communication, then the state-of-the-art knowledge on community-scale safe drinking water supply (Section 3). A selection of point-of-use water treatment systems and their estimated costs are then discussed.

2. Methodology

The literature research has not adapted any systematic approach for a literature review, for example, by using several search terms and combinations thereof to identify the scientific literature related to frugal systems for small-scale safe drinking water provision. The used references were rather selected for their suitability to address the subject based on two decades of active research on “decentralized safe drinking water supply”. The communication is motivated by the following three key issues: (i) decentralized water supply systems are usually perceived as more costly than centralized systems, mostly due to a lack of consideration of the avoided costs, including the local manpower [44], (ii) many so-called innovative solutions are based on materials and principles that have been used for the same purposes for more than one century [10], and (iii) slow sand filtration (SSF) systems installed in European cities (e.g., Berlin, Paris) continue to operate today [45–47]. Early in the 20th century, SSFs lost their popularity, mostly because of the large space demand. SSFs were replaced by rapid sand filters (RSFs), which are coupled with chemical coagulation.

It is certain that the cost perspective widely depends on the stakeholder performing the economic analysis (e.g., developers, community of users, water agency) [44]. In this communication, cost comparison is based on a very recent cost analysis in a paper entitled “Economic evaluation of water supply systems operated with solar-driven electro-chlorination in rural regions in Nepal, Egypt and Tanzania” [3]. Covering three geographically distant countries, the analyses are practical and relevant for most of the situations in the developing world. The named cost evaluation [3] is also important because it addresses the relevance of subsidies by governments and international organizations in achieving “safe drinking water for all”.

A great variety of safe drinking water supply technologies are available on the market [3,31,47]. Technological innovation continuously seeks to adapt or develop decentralized systems to the current needs of small communities [44]. Such technologies are usually developed at the niche level. Ideally, technological improvements should be directed at reducing maintenance requirements and reducing costs. New decentralized designs of water treatment should also be context-specific since system requirements differ significantly from place to place. All these criteria are important to select technology for the rural areas of developing countries where the procurement of materials is critical to achieve a sustainable water supply (Table 1).

Table 1. Main features of commercial and self-designed (frugal) decentralized safe drinking water supply systems.

Factor	Commercial Treatment Unit	Frugal Treatment System
Participation	Very limited public participation	Active public participation
Awareness	Citizens alienated from know-how	Citizens mastering the design and operation
Funding	Highly subsidized	Mostly full cost recovery, and low-cost
Resilience	Limited adaptation to changes	Enhanced adaptation to changes
Social conflicts	More likely	Less likely
Water quality	High for selected species	Adaptable and fit-for-purpose

3. Community-Scale Safe Drinking Water Supply

Decentralized systems for safe drinking water provision are an essential element in efforts to achieve Goal 6.1 of the Sustainable Development Goals of the United Nations (“drinking water for all”). This is mainly because centralized systems are non-existent in remote and scattered communities, mostly in developing countries [2,48,49]. The current paradigm considers that biological contamination is the most important problem in these communities due to the universal prevalence of pathogens [2,3,31,38]. Accordingly, a wide range of decentralized water treatment systems are available for water disinfection only. These include chemical (e.g., chlorination) [3], physical (e.g., filtration) [50,51], and thermal treatment methods (e.g., boiling, pasteurization) [29], and a combination thereof [40,52]. However, considering the increasing universal use of chemicals including those of emerging health concern (e.g., pharmaceuticals and personal care products), it has been recently demonstrated that contamination by synthetic chemicals is increasingly of worldwide concern [32,53,54]. This is in addition to well-known toxic geogenic contaminants such as radionuclides (e.g., U), arsenic, and fluoride, among others. Yet, current decentralized technologies for water treatment have a limited capacity to remove dissolved synthetic and geogenic contaminants [55]. For example, water disinfection by boiling may even increase the concentrations of toxic geogenic contaminants. Chlorination may generate human carcinogens in the presence of natural organic matter and has a limited capacity to remove dissolved contaminants. Consequently, decentralized safe drinking water systems should address both biological and chemical contamination [32,52,53]. Moreover, the quality of treated water should be assessed (or confirmed) using instrumental water analysis [54,56–58]. This calls for a shift in the present paradigm in developing countries that places emphasis on the water supply (e.g., via drilling of boreholes) with limited consideration for the analytical testing and treatment of such water. Excluding water testing and treatment in the water supply paradigm exposes humans to synthetic (e.g., pesticides) and geogenic contaminants (As, F, U). Thus, the need for the universal testing of drinking water has been discussed in a recent paper calling for the development of a water quality and quantity index (WQQI) [59]. Such a WQQI should be supported by the establishment of Water Applied Testing and Environmental Research (WATER) Centers [59]. Yet, most developing countries, including those in Africa, still lack the analytical infrastructure for the basic testing of drinking water.

The current presentation focuses on decentralized or point-of-use (POU) systems for safe drinking water provision at a community-scale. Household systems are excluded because monitoring their operation is very difficult [5,60–63]. However, the generic approach for the development of modular water treatment systems discussed here can be downscaled to the household level. Regarding appropriate water treatment technologies, important boundary conditions for the developing world include [2,40,60] (i) robustness or consistency in performance, (ii) low implementation and running costs, (iii) ease of use and repair with no need for external special skilled personnel, (iv) ability to function without electricity (grid-independent), (v) based on local resources and skills, (vi) low maintenance, and (vii) should fit into the socio-cultural settings, including the capacity for women and girls to use and repair such technology. These conditions correspond largely to those of emergency water supply [63], with the subtle but essential difference that the population is available to co-design their own water treatment systems [19].

The modular treatment chain presented by Aqueous Solutions (www.aqsolutions.org, 25 May 2021), and the opportunity to independently replace individual treatment units (e.g., biochar filter, Fe⁰/sand filter) almost eliminate the limitation of frequent and time-consuming maintenance operations. For example, if the capacity of the biochar filter is exhausted, its replacement can be organized and operated in a few hours without disrupting the daily water supply. Note that, systems based on imported devices and components are explicitly excluded in the present discussion (Section 2). This excludes membrane technologies [51] and other robust systems that can be powered by solar energy (off grid) [3,38,64]. Chlorination and other chemistry-based water treatment methods

are equally excluded due to their over-reliance on chemicals not readily available to communities.

This communication is not addressing the issue of water availability, but rather focuses on the treatment. There are various water sources depending on the geographic situation and some historical and cultural considerations. In principle, there are the following three sources of water for treatment: (i) rainwater, (ii) surface water, and (iii) groundwater [7]. As groundwater is present everywhere, the groundwater depth makes the difference, thus, borehole drilling can make water available [65]. It is considered that off-grid pumping (e.g., using solar or wind energy, and manual methods) will be used to pump water from wells into the storage tank and the rest of the system will be gravity driven [66]. According to the literature, water treatment trains comprising of biochar (BC) and/or metallic iron (Fe^0) are able to transform any polluted water into safe drinking water [32,34–36,52,53,55]. In other words, using natural geomaterials (e.g., gravel, pumice, sand), BC and Fe^0 can provide safe drinking water everywhere. While Kearns and colleagues [32,35,53] have developed and popularized tools to produce cost-effective BC everywhere, affordable Fe^0 materials are also universally available, for example as steel wool [67–69].

The last important feature for the health of the community is water disinfection, in terms of preventing treated water being re-contaminated with pathogens [2,63,70]. The first thing to consider is that the universally used water chlorination is not safe [71–73]. This is particularly challenging under conditions where there is a lack of technical skills for proper dosage. Chlorination has been banned in The Netherlands in 2005 because of health issues [72,74], but is still recommended by the World Health Organization (WHO), especially in low-income countries lacking advanced water treatment technologies [3]. The question then arises: *How do we cope with this issue and its potential human health risks?* The answer is simple, this study is targeting small communities, where members can be educated to drink treated water within three days after treatment to avoid re-contamination [60]. After this timeframe, treated water should be used for other purposes, including cooking. A viable alternative is the pasteurization of treated water twice or three times per week. This option is particularly recommendable where stored rainwater is the source of water. Solar pasteurization (SOPAS) can be used as a stand-alone water treatment technology where there is no chemical contamination. However, an affordable SOPAS for community water supply is yet to be designed [66,75].

4. Affordability and Sustainability of Selected Point-of-Use Water Treatment Systems

Until now, the presentation has focused on POU systems as key solutions for safe drinking water provision in low-income communities (Section 3). Many POU systems have been developed and used in the last few decades; hence, this review gives an overview of the existing POU systems for small communities while insisting on those meeting the exclusion criteria (chemistry-free, grid-independent, locally available expertise, and materials). The aim is to recall the operating mode of relevant technologies and then discuss their affordability. Interested readers are referred to the abundant literature on POU systems for clean water in emergency situations [2,3] and for developing countries [63].

Table 2 presents a timeline of key events in the development and application of SSFs, particularly for small community water supply. In summary, as early as 1804, the efficiency of SSFs in water treatment was demonstrated in Scotland. Subsequent work conducted up to 1886 witnessed the applications of SSFs and Fe^0 -based systems for water treatment in a number of other countries including Belgium, Egypt, England, France, and India. Thereafter, SSFs, biological sand filters (BSFs), and Fe^0 -based water filtrations were developed almost independent of each other (Table 2). Biochar-based water filtration systems started to emerge around 2014 to 2017, following the work of Kearns et al. [35]. During the same period, the University of Idaho developed and patented N-E-W Tech™, a biochar-based reactive filter system (www.uidaho.edu/news/here-we-have-idaho-magazine/pastissues/2015-fall/greg-moller/, accessed on 29 July 2021). The N-E-W Tech™ is a high-flow system that can be adapted to have a throughput ranging

from a few gallons per minute to tens of millions of gallons per day (www.uidaho.edu/news/here-we-have-idaho-magazine/pastissues/2015-fall/greg-moller/, accessed on 29 July 2021). A subsequent seminal review further popularized biochar-based water filtrations as a sustainable and low-cost technology for drinking water supply in low-income countries [55].

Table 2. Timeline of major events in the field of slow sand filtration (SSF) research and its adaptation to small community water supply.

Anno	Event	Refs.
1804	Demonstration of the efficiency of SSFs by John Gibb in Paisley (Scotland)	[10]
1829	Adoption of SSFs for the water supply of Chelsea (London/England)	[10]
1881	Fe ⁰ amended SSFs for the water supply of Antwerp (Belgium)	[76]
1883	Fe ⁰ -based revolving purifier for the water supply of Antwerp (Belgium)	[77]
1886	SSFs demonstrated to remove bacteria by Frankland	[78]
1951	Domestic steel wool water filters for radionuclides removal	[79]
1980s	Renewed interest in SSFs for small and medium communities	[45,47]
1985	Schmutzdecke shown to remove coliforms by Bellamy	[45,47]
1992	Down-scaling of SSFs for the domestic needs by David H. Manz (BSFs)	[80]
1990s	Attempts to improve the efficiency of SSF by reinforcing biological activities	[81,82]
2000	Fe ⁰ amended BSFs for the As and pathogen removal in Bangladesh	[83]
2006	Development of Kanchan Arsenic filters in Nepal	[84]
2007	Development of SONO Arsenic filters in Bangladesh	[85]
2008	Development of IITB Arsenic filters in West Bengal (India)	[37,40]
2010	Fe ⁰ amended BSFs for the As, pathogen, and U removal in rural Canada	[39]
2012	Efficiency of Kanchan Arsenic filters disproved	[86]
2012	Adoption of SSFs for the water supply in rural Switzerland	[87]
>2012	Implementation of several aggregate-amended SSFs for rural water supply	[52,88]
2016	Development of the modular SSF/biochar filters for rural water supply	[35,89]
2019	Domestic steel wool-based water filter operating for one year	[43,68]

Before presenting the technologies and discussing their costs, it is important to recall the key points related to clean water provision. Cities in developed countries are supplied with drinking water provided via conventional centralized water treatment systems. Centralized water supply systems are often owned by the municipalities or private organizations that are working on their behalf. Treated water is distributed to households via piping systems and citizens pay tax for drinking water and the resulting wastewater. Still, in the developed world, where the density of population is too low and the tax money cannot enable affordable safe drinking water, a decentralized water supply is organized and controlled [90–92]. This approach motivated the renewed interest for slow sand filters (SSFs) in the Western World during the 1980s (Table 2) [93]. Recently, Jepson and Vandewalle [92] maintained that the view that households in developed countries have universal piped indoor water is a pervasive one. In the United States, for example, more than 600,000 households must struggle daily for outdoor safe drinking water. The concerned mostly low-income rural communities (e.g., on the Texas–Mexico border) are regarded as “marginalized communities” with regard to access to safe drinking water. However, there are reliable programs to alleviate household water insecurity and the population largely has access to water of drinking quality at some reasonable distance from their homes.

In developing countries, however, the upfront cost of centralized water treatment and distribution systems hinder their installation even in densely populated cities and peri-urban areas [3]. Moreover, due to weak governance systems and poor accountability, the taxes paid for water are often not invested back to improve water infrastructure. As a result, water infrastructure progressively deteriorates against a background of increasing water demands driven by rapid population growth and rural–urban migration. POU technologies are on-site water treatment systems that address this situation.

The relevant POU technologies are coagulation/flocculation, disinfection, and filtration [3,8]. Flocculation and coagulation use chemicals (non-chemistry-free) to remove the contaminants and turbidity. Disinfection kills pathogens by heating or the addition of chemicals. Heating can be achieved by firewood or fossil fuels. However, the current conventional disinfection methods such as chlorination are not chemical free, while the critical shortage of firewood and fossil fuels, and the associated costs, may constrain heating/boiling. From the three possible principles highlighted, only filtration remains as the candidate technology meeting the criteria. In other words, self-reliance in safe drinking water supply depends on the ability to design gravity-driven filtration systems capable of freeing polluted waters from biological, chemical, and physical contamination. Filtration basically removes contaminants by size exclusion, whereby particles and species larger than the pore size of the filter are retained within the system [2,8,34,94,95].

The filtration technologies implemented at the POU are mainly slow sand filtration (SSF) and membrane filtration [3,51,63]. Membrane filtration is excluded herein because it is not always grid-independent, and in most low-income countries, membranes are not fabricated locally (Table 1). In other words, SSF and their modifications could transform polluted water to drinking water everywhere (Table 2). SSFs are easily constructed using raw materials that are locally sourced. Over the past few decades, the amendment of SSF with adsorbing (e.g., biochar, granular activated carbon, metal oxides) and reactive (e.g., MnO₂, metallic iron) materials have improved their capacity at removing pathogens and various classes of chemical contaminants [34,52,55,96,97].

Since 2006, the research group of Dr. Noubactep (Göttingen, Germany) has been continuously working on ways and means to make Fe⁰-based systems a universal solution for decentralized safe drinking water provision [34,97]. The state-of-the-art knowledge is that filtration on Fe⁰ beds sandwiched between SSFs will eliminate all the naturally occurring contaminants except fluoride [98,99]. However, bone char is an affordable material of choice for fluoride removal [100] and the odors from the bone char filtration are eliminated by Fe⁰ filtration. Thus, a multiple barrier system comprising bone char, Fe⁰/sand, and SSF, designed on a site-specific basis, can be developed for clean water production. A biochar barrier (BC unit) can be part of this treatment train. During the past 15 years, Kearns and colleagues have demonstrated the particular suitability of BC units to generate safe drinking water from organic- and pathogen-laden natural waters [32,35,42,53].

As a proponent of technology co-development, Dr. Josh Kearns has developed and published on YouTube a modular and adaptable water treatment train with translation in many languages. This demonstration is regarded by the authors as the key for universal self-reliance in safe drinking water provision. The evidence shows that in most cases, research laboratories at local universities in low-income countries have tested the suitability of most locally available materials (e.g., geomaterials, biomaterials) for the remediation of common contaminants in local water sources [43,58]. Thus, one just needs to replace the biochar unit in Figure 1 with a relevant locally available bio- or geo-material and test its operational efficiency and sustainability. If this approach is adopted immediately everywhere, there is no doubt, the Goal 6.1 of the UN SDGs will be achieved by 2030.

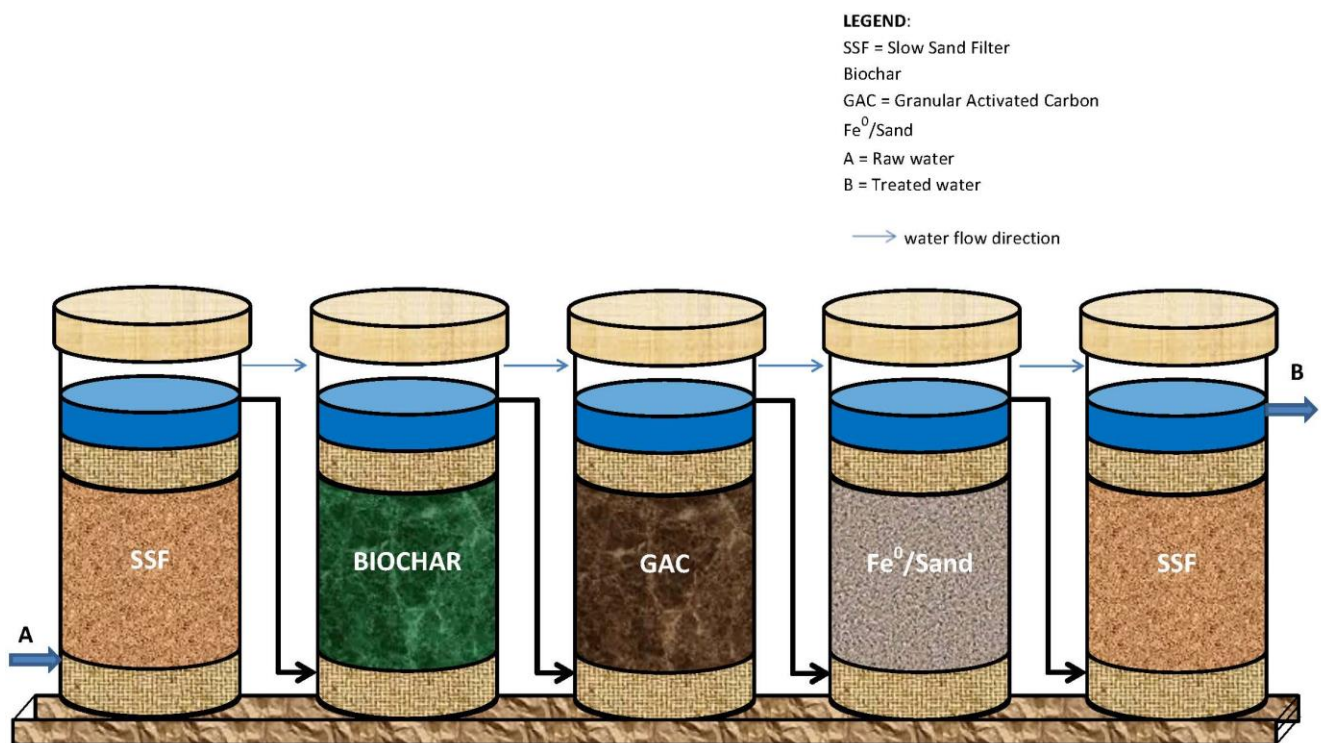


Figure 1. Possible water treatment train for a small-scale plant. Here, the following three units for the removal of chemicals are presented: biochar, granular activated carbon (GAC), and Fe⁰/sand. The three units are sandwiched between two slow sand filters (SSFs). Water from the second SSF is stored for distribution.

A closer examination of the four technologies in Table 3 further shows several merits of biochar and Fe⁰ water filtration systems. Biochar and Fe⁰ have no or limited adverse effects on the taste of water, unlike chlorination. Biochars can be locally prepared using low-cost pyrolysis systems and readily available biomaterials. Chlorination has the potential to generate carcinogens in the presence of natural organic matter, a common constituent in most natural waters. Biochar and Fe⁰ filtration systems are gravity driven, and hence require biochar produced via pyrolysis using local and readily available feedstocks and materials (e.g., used drums, pit kilns, biochar cookstoves) [55,101]. Similarly, most low-income countries in the Global South have large reserves of iron ore, hence Fe⁰ is readily available at a nominal cost. The proposed systems are less sophisticated than imported ones [3,38,51]; hence, they are easier to install and repair at a local level by community members including women and girls, without the need for external experts from far-away cities/towns and foreign countries. Due to these several merits, such technologies may fit the socio-economic settings in most low-income countries better than imported technologies [18,19]. Overall, the nominal cost of the proposed technology is several orders of magnitude lower than the several thousands of dollars used by NGOs and governments in effort to provide clean drinking water. Moreover, the proposed technology should be integrated into the water supply systems including cases where boreholes have been drilled in highly mineralized geological systems rich in toxic geogenic contaminants without addressing the water quality aspects. Taken together, the proposed point-of use treatment systems warrant pilot testing in low-income countries.

Table 3. Comparison of investment, installation, and running costs for four small-scale water supply systems using (i) biochar, (ii) metallic iron (Fe^0), (iii) PAUL, and (iv) Autarcon (chlorination). All costs that are equal for all systems are operationally considered to be zero (available). The Autarcon system needs energy for in situ generation of chlorine and addresses only microbial contamination. PAUL stands for “Portable Aqua Unit for Lifesaving” and is a membrane-based technology producing up to 1200 L/d. One PAUL costs 1000 Euro, two are used to cope with the community water requirements (2000 L/d).

	Biochar	Metal Iron	PAUL	Autarcon
	(Euro)	(Euro)	(Euro)	(Euro)
Reference	[49]	[96]	[51]	[3]
Water availability (e.g., well drilling)	0.0	0.0	0.0	0.0
Building infrastructure	0.0	0.0	0.0	0.0
Water pumping	0.0	0.0	0.0	0.0
Water supply system	0.0	0.0	0.0	0.0
Material cost (O & M)	1000	1250	0	13,500
Water treatment system (WTS)	1500	2000	2000	12,000
Energy supply	0	0	0	500
Installation (labor)	0	0	0	3500
Operation and Maintenance (per year)	0	0	0	1004
Transport of WTS	0	0	200	1000
Customs duty	0	0	100	3910
Spare parts (per year)	0.0	0.0	0.0	917
Total costs	2500	3250	2300	36,331
Ratio Autarcon/X	14.5	11.2	15.8	1.0

5. Sand Filtration Systems: The Partly Overlooked Universal Solution

The presentation until now can be regarded as a re-demonstration of the suitability of SSFs for water treatment at the small community level. This section reveals that this task has already been realized several times. It suffices to recall the history of slow sand filters (SSFs), biological sand filters (BSFs), and their amendment with various materials (Table 2) in the following four points

(i) Slow sand filters are considered as the oldest community-scale water treatment technology. The first SSF was demonstrated by John Gibb in 1804 in Paisley (Scotland). In 1829, a SSF was adopted for a public water supply at the Chelsea Water Company in London [90,93,102–104]. Since then, SSFs have been widely used in water treatment plants for the inactivation and removal of microorganisms [52,90]. However, SSFs alone will not be able to produce water that is free from bacteria and viruses. Therefore, further treatment such as disinfection is always needed. One ancient water disinfectant is metallic iron (Fe^0) [8,9].

(ii) SSFs amended with Fe^0 (Fe^0 SSFs) were used to successfully supply the city of Antwerp (Belgium) with safe drinking water from 1881 to 1883 [105]. The systems worked without maintenance for 18 months. At that time, the city of Antwerp then had 200,000 inhabitants. This means that supplying up to 200,000 people with safe drinking water from Fe^0 -amended filters is a 140-year-old technology. Today, in most cases, the challenge is to supply some small communities with less than 20,000 inhabitants, 10 times lower that population of Antwerp in 1883. Clearly, Fe^0 SSFs can supply adequate clean drinking water to typical small communities.

(iii) In the early 1990s, Dr. David H. Manz developed a hypothesis that enabled the scaling down of SSFs and their adaptation to intermittent small community and household filters, termed as biological sand filters (BSFs) [102,106,107]. The effectiveness of BSFs in

quantitatively removing fecal coliform indicators was then demonstrated, and the need of improved pathogen removal established. Similar to SSFs, Fe⁰-amended BSFs (Fe⁰ BSFs) were proven efficient for safe drinking water provision [67]. During the past decade, experimental investigations have identified design and operation recommendations to improve the effectiveness of the next generation of Fe⁰-amended BSFs [68].

(iv) SSFs were abandoned in the early 20th century because their low hydraulic loading rate and large drinking water volumes required for large populations was only possible with large areas. This limitation has led to the adoption of rapid sand filters (RSFs) after coagulation and flocculation [7]. However, there is strictly no such land scarcity in the rural areas of developing countries for SSFs, meaning that the installation of SSFs is still an option in many cases. However, the relatively low drinking water demand can still be satisfied by community-scale BSFs. It is interesting to note that such filters are operating in the developed world, for example in rural Switzerland [108,109], pointing to the possibility to develop and implement similar systems in developing countries [99–110].

To summarize, SSFs and BSFs are affordable water treatment systems whose relatively high efficiency for pathogen removal is well-documented. However, their inefficiency for the removal of chemical contamination (e.g., synthetic organic substances, heavy metals) are known and well-documented. Both systems have been improved by amendment with other materials, including Fe⁰ [110]. The question arises, “*why has the search for frugal solutions for safe drinking water not started by this universal solution?*”. There is no unique answer to this question, but it is time to retrace the steps to this simple technology, and start solving drinking problems, and achieve the Sustainable Development Goal 6.1 with the readily available means. Table 4 summarizes the capability of BC- and Fe⁰-amended SSFs for safe drinking water provision. The details of the removal efficiencies and mechanisms for specific types of dissolved organic and inorganic contaminants, pathogenic organisms, and suspended solids are given in the literature summarized in Table 2. Hence, for brevity, these aspects are not repeated in the present paper. Here, only a summary of the performance is given. This recall is regarded as an appeal for any developer. The article advocates that any new development should be frugal and shall demonstrate how it surpasses these achievements.

Table 4. Comparison of the efficiency of slow sand filters (SSFs), single aggregate filters and two amended SSFs for the removal of chemicals, odors, and pathogens. + stands for low, ++ for good, and +++ for excellent. Efficient frugal water treatment systems are possible everywhere, as BC and Fe⁰ are universally affordable and available.

Technique	Expertise (Years)	Removal Efficiency for		
		Chemicals	Odors	Pathogens
SSF	190	+	++	++
Fe ⁰	>160	++	+++	+++
Biochar	20	+++	+++	++
Bone char	>160	+++	+++	++
Fe ⁰ SSF	150	+++	+++	+++
BC SSF	15	+++	+++	+++

6. Conclusions

An overview of the affordability and effectiveness of water treatment options to provide small communities with safe drinking water is given. Relevant water treatment options include chemical treatments (e.g., chlorination), ecological treatments (e.g., slow sand filtration), physical treatments (e.g., filtration), thermal treatments (e.g., heating, and ultraviolet radiation), and hybrid treatment chains (e.g., multiple barrier approach). The objective was to assess whether frugal (chemistry-free, electricity-free) technologies for self-reliance in safe drinking water supply are already available in the literature (Tables 2 and 4).

The results indicate that the multiple barrier approach presented by Dr. Kearns is affordable and adaptable to any situation. The site-specific adaptation depends not only on the nature of polluted water but also from the available expertise. For example, a community that has expertise with GAC will preferentially replace the biochar unit (Figure 1) with a GAC unit, while a community with fluoride contamination will add a bone char or activated alumina unit. Fe⁰/sand units can be added both for main treatment and for affinage, for example, in this case, fluoride free water from a bone char unit should be freed from odors [52].

This study shows how self-assembled community-scale water filtration devices can universally solve the long-lasting problem of unsanitary drinking water conditions. In the Global South in general and Africa and South East Asia in particular, a legitimized, long-term solution for “own” safe drinking water is presented (Table 4). In other words, two independent research groups one led by Dr. Josh Kearns working in Thailand and another by Prof. Chicgoua Noubactep conducting work in Cameroon/Tanzania have demonstrated the feasibility of self-reliant, small-scale water treatment systems during the last 15 years. These findings rapidly mitigate water insecurity worldwide [32,35,42,50,53,98,99]. Interestingly, such systems will find applications also in developed countries, for example in solving “chronic” household water insecurity in Texas/USA [70,92]. The large-scale field implementation of these findings is up to engineers, public health research scientists, and universities in the Global South who can best assess and address the local conditions of their residents. Of course, national and international NGOs can support these efforts. Scientists from other regions of the world can support these efforts. It should be explicitly said that any effort to continue the development of non-frugal technologies for the developing world is contra productive. It is definitively not worth the effort to design water treatment units for the Global South in which transport costs are more expensive than the installation of alternative units accomplishing the same task (Table 3). It is hoped that this communication opens an avenue for the achievement of Goal 6.1 of the SDGs, while inaugurating a new area for drinking water governance in the Global South.

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Abbreviations

BC	Biochar
BSF(s)	Biological sand filter(s)
Fe ⁰	Metallic or zero-valent iron
GAC	Granular activated carbon
RWH	Rainwater harvesting
NGO	Non-governmental organization
O & M	Operation and maintenance
POU	Point-of-use
RSF(s)	Rapid sand filter(s)

SDG	Sustainable Development Goal
SOPAS	Solar pasteurization
SSF(s)	Slow sand filter(s)
WATER	Water Applied Testing and Environmental Research
WQQI	Water Quality and Quantity Index
WTS	Water treatment system

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