Kanchan Arsenic Filters and the Future of Fe0-Based Filtration Systems for Single Household Drinking Water Supply

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Date Submitted: 2021-10-11

Keywords: zero-valent iron, removal efficiency, household filter, groundwater contamination, arsenic removal

Abstract:

Biological and chemical contamination of natural water bodies is a global health risk for more than one billion people, mostly living in low-income countries. Innovative, affordable, and efficient decentralized solutions for safe drinking water supply are urgently needed. Metallic iron (Fe0)-based filtration systems have been described as such an appropriate solution. This communication focuses on the Kanchan arsenic filter (KAF), presented in the early 2000s and widely assessed during the past decade. The KAF contains iron nails as the Fe0 source and is primarily designed to remove As from polluted tube well waters. Recent independent works assessing their performance have all reported on a high degree of variability in efficiency depending mostly on the following factors: (1) the current operating conditions, (2) the design, and (3) the groundwater chemistry. This communication shows that the major problems of the KAF are two-fold: (1) a design mistake as the Fe0 units disturb the operation and functionality of the biosand filter, and (2) the use of poorly characterized iron nails of unknown reactivity. This assertion is supported by the evidence that the very successful community filter designed by the Indian Institute of Technology Bombay works with iron nails and has been efficient for many years. Replacing iron nails by more reactive Fe0 materials (e.g., iron fillings and steel wool) should be tested in a new generation KAF. It is concluded that a methodological or systematic approach in introducing and monitoring the efficiency of KAF should be used to test and disseminate the next generation KAF worldwide. Moreover, better characterization of the Fe0 materials including their intrinsic reactivity is required.

Record Type: Published Article

Submitted To: LAPSE (Living Archive for Process Systems Engineering)

Citation (overall record, always the latest version):	LAPSE:2021.0753
Citation (this specific file, latest version):	LAPSE:2021.0753-1
Citation (this specific file, this version):	LAPSE:2021.0753-1v1

DOI of Published Version: https://doi.org/10.3390/pr9010058 processes

MDPI

Communication

Kanchan Arsenic Filters and the Future of Fe^0-Based Filtration Systems for Single Household Drinking Water Supply

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Abstract: Biological and chemical contamination of natural water bodies is a global health risk for more than one billion people, mostly living in low-income countries. Innovative, affordable, and efficient decentralized solutions for safe drinking water supply are urgently needed. Metallic iron (Fe^0)-based filtration systems have been described as such an appropriate solution. This communication focuses on the Kanchan arsenic filter (KAF), presented in the early 2000s and widely assessed during the past decade. The KAF contains iron nails as the Fe^0 source and is primarily designed to remove As from polluted tube well waters. Recent independent works assessing their performance have all reported on a high degree of variability in efficiency depending mostly on the following factors: (1) the current operating conditions, (2) the design, and (3) the groundwater chemistry. This communication shows that the major problems of the KAF are two-fold: (1) a design mistake as the Fe^0 units disturb the operation and functionality of the biosand filter, and (2) the use of poorly characterized iron nails of unknown reactivity. This assertion is supported by the evidence that the very successful community filter designed by the Indian Institute of Technology Bombay works with iron nails and has been efficient for many years. Replacing iron nails by more reactive Fe^0 materials (e.g., iron fillings and steel wool) should be tested in a new generation KAF. It is concluded that a methodological or systematic approach in introducing and monitoring the efficiency of KAF should be used to test and disseminate the next generation KAF worldwide. Moreover, better characterization of the Fe^0 materials including their intrinsic reactivity is required.

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Citation: Huang, Z.; Cao, V.; Nya, E.L.; Gwenzi, W.; Noubactep, C. Kanchan Arsenic Filters and the Future of Fe^0-Based Filtration Systems for Single Household Drinking Water Supply. *Processes* **2021**, *9*, 58. https://doi.org/10.3390/pr9010058

Received: 6 December 2020
Accepted: 25 December 2020
Published: 29 December 2020

1. Introduction

This communication is motivated by recent reports assessing the sustainability of Kanchan arsenic filters (KAF) for safe drinking water provision in rural Nepal [1–3]. The removal of pathogens, micro-pollutants, and turbidity from polluted waters using reactive filtration systems involving metallic iron (Fe^0) is well-established [4–11]. In particular, Fe^0-based filtration systems have been efficient in removing iron, manganese, phosphates, and several organic micro-pollutants (e.g., fertilizers, pesticides, nitrates, pharmaceutical and personal care products, and phosphates) from polluted waters [4–7,9]. Hence, Fe^0 certainly has some favorable prospects in mitigating hazards from arsenic and pathogen contamination, thereby making it an economically attractive technology [6,7,12,13].

Such an affordable technology is urgently needed in areas where natural water is polluted by geogenic As [2,3,6,11]. The large extent of As polluted groundwater sources in more than 30 countries and the lack of financial capacities for advanced water treatment technologies render conventional centralized water treatment approaches almost void [14–20]. Hence, As removal at household level by engineered point-of-use devices based on some readily available and cheap forms of Fe^0 as filter medium (e.g., iron nails, scrap iron, and steel wool) promises to be an economically beneficial alternative [7,13,21]. The KAF containing iron nails is such a promising solution [22,23]. However, available reports on As removal by KAFs seem rather univocal and overly generalized on their As removal efficiency [2,3,24–28]. In particular, Smith et al. [27] demonstrated that iron nails placed in biosand filter (BSF) were more effective than those placed above. Some other suggestions to improve the KAF have been presented which collectively can be regarded as complications of the original KAF to the extent that it becomes maintenance-intensive, and thus inapplicable for the target end-users [1–3].

This short communication reveals that the KAF contains design mistakes: (i) its Fe^0 unit depletes oxygen and disturbs the formation of the biofilm layer, and functionality of the biological sand filter (BSF), and (2) the used iron nails are not reactive enough to warrant sustainable As removal. If these mistakes are corrected, the resulting design(s) could be rapidly developed into a sustainable solution of worldwide applicability [27]. In this effort, all other components of the KAF concept (social acceptability, dissemination, monitoring) will be simply used or slightly adapted [23]. Being part of a special issue containing a tutorial review on the Fe^0/H_2O system [29] and a conceptual article on designing Fe^0-based filters [13], the present communication is limited to addressing flaws in the assessment of the sustainability of KAFs. Much of the impetus for this discussion has come from two recent works [2,3], which have suggested some tools for the improvement of the conventional KAF. The premise that the conventional KAF contains a design mistake is mainly supported by independent experimental results by Smith et al. [16,25,27], comparing KAF and SONO filters for water treatment, including As removal, and presenting the latter as an "excellent technology for safe water in Nepal" [16]. In other words, the groundwater geochemistry in Nepal could have a lesser impact on the KAF as previously considered [1–3].

The objectives of the current communication are as follows: (i) to present a critique of the design and functionality of the KAF, and (ii) to propose improvements to enhance the functionality and efficiency of the KAF. The presentation starts by a description of the KAF, followed by a critical assessment of its functionality, and finally, suggested improvements and future research directions.

2. The Kanchan Arsenic Filter

The Kanchan arsenic filter (KAF) as originally presented [22] uses a combination of iron nails and sand in a compact device to remove arsenic and pathogens from natural water (Figure 1). The KAF resulted from five years of intensive investigations, including fieldwork in Nepal. It was developed in Nepal as a joint venture between Massachusetts Institute of Technology (MIT–Massachusetts/USA), Environment & Public Health Organization (ENPHO–Kathmandu/Nepal), and Rural Water Supply and Sanitation Support Programme (RWSSSP) of Nepal [2].

A KAF consists of a large bucket in which water is poured in from the top and passes through the following layers: (1) a bed of iron nails (Fe^0 unit), and (2) a sand bed (sand unit). Ideally, arsenic, iron, micro-pollutants, and turbidity are removed in the Fe^0 bed, while pathogens are removed in the sand layer, acting as a conventional biosand filter [3,22,23,27,30]. A KAF can intermittently filter 15–20 L d^{-1} [23,25,30]. The maintenance operation of a KAF consists of cleaning the filter in bucket between once a month to twice per year. The frequency of maintenance depends largely on the initial water quality [3,30].

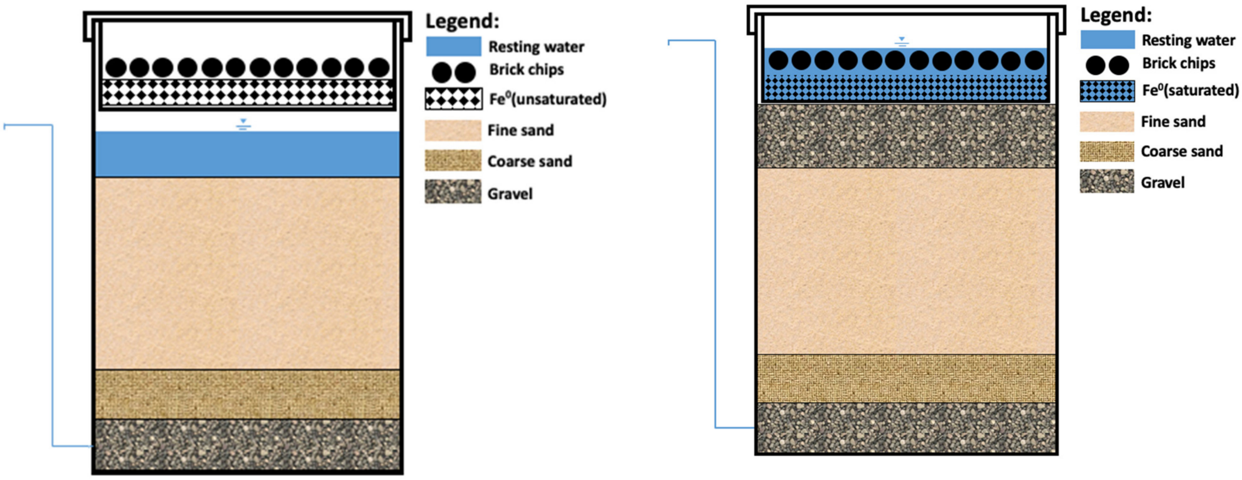

Figure 1. (**left**) Diagram of the original Kanchan arsenic filter (KAF). The location and arrangement of its components are depicted (adapted from [23]). (**right**) Modification of the original KAF to immerse the Fe^0 unit. A gravel layer separates the sand unit from the Fe^0 unit.

The first design mistake of the KAF device is certainly the existence of a non-immersed Fe^0 unit which creates a dry/wet cycle for the iron nails [1,2]. This is counter-intuitive in a context where long-term increased iron corrosion is needed for As removal [21]. The dry/wet cycle also favors the creation of preferential flow paths which limits the interactions between As and the generated hydrous ferric oxide (HFO). To correct this mistake, Figure 1 (right) suggests the immersion of the Fe^0 unit by elevating the outlet pipe above this unit. While this modification is yet to be tested, Mueller et al. [2] reported on some improved As removal by avoiding a scenario where the Fe^0 unit goes completely dry.

It is very important to note that there is no evidence on the impact of the dry/wet cycle on iron corrosion under conditions comparable to those occurring in KAFs in Nepal. It is well-established in the atmospheric corrosion science that Fe^0 is corroded in humid environments and the corrosion rate increases with increasing relative humidity. This is because humidity (H_2O) acts as a solvent for corrosive species like CO_2, O_2, or SO_2 to produce the electrolyte which is required for setting up a corrosion cell. In other words, humidity or moisture is the electrolyte and the corrosivity is increased by the presence of dissolved species (e.g., CO_2 and O_2) [31,32]. Clearly, a rise in humidity increases the rate of corrosion. This evidence questions the rationale of introducing a wet/dry cycle in the design of KAF.

It should also be noted that a wet/dry cycle intensifies corrosion in saline environments because of high salinity [33,34]. In fact, with the setting of the dry period (evaporation), there is an increased salt concentration (ionic strength) in the Fe^0 vicinity. This high salt level accelerates O_2 transport across the thin electrolyte layer, and delays the formation of Fe hydroxides at the setting of the wet period. Such an effect is not expected with groundwaters from rural Nepal and elsewhere.

Despite 16 years of existence, the KAF is still considered as an innovative household filter for removing arsenic, iron, micro-pollutants, pathogens, and turbidity from natural waters [1–3]. The KAF is said to combine slow sand filtration and iron hydroxide adsorption principles in one compact device [2,3,22,23]. This filter was developed in a multi-disciplinary research approach and is optimized by taking into account the socio-economic conditions in rural Nepal [22,23]. Two versions of the KAF have been initially promoted in Nepal: Plastic round and concrete square. In the meantime, five different versions exist [2,3]. The five versions differ in their form (round or square), and in the nature of the container (concrete or plastic). Plastic KAFs are lightweight and cheap, while the concrete version is more durable and suitable for a long-term deployment. Figure 1 (right) also depicts a modification of the conventional KAF which would certainly enhance its efficiency because the Fe^0 unit is completely immersed (Section 4).

3. The Design Limitations of KAF

The view that the conventional KAF combines slow sand filtration and iron hydroxide adsorption principles has been challenged eight years ago [35], but has been largely ignored in subsequent studies discussing the sustainability of KAF [1–3,26]. A slow sand filtration needs dissolved oxygen (O_2) to operate properly [13]. This is because dissolved oxygen is required for the formation of a biofilm (Schmutzdecke) in the biosand filter (BSF). The biofilm removes pathogens mostly by predation [36–39]. In the KAF, however, O_2 is ideally depleted in the Fe^0 unit before it even reaches the sand bed (the supposed BSF). In fact, this ancient knowledge that Fe^0 as O_2 scavenger has been recalled and exploited in the Fe^0 literature prior to the advent of KAF [40,41]. In other words, if pathogens are quantitatively removed in KAFs, this removal also occurs in the Fe^0 bed, like in the Anderson Process [4] or in the community-scale filter of the Indian Institute of Technology, Bombay (ITTB filter) [42–45].

The IITB filter was conceptualized using the evidence that As removal is enhanced by in-situ generation of Fe^{II} species which are oxidized by dissolved O_2 to produce very adsorptive hydrous ferric oxide (HFO). Moreover, sand is not used in the Fe^0 unit to avoid loss of nascent iron hydroxides which would coat sand and not be available for As removal [42,45]. IITB systems have been installed in several villages in the West Bengal [45], all of which are performing very well, even after 10 years. The success of IITB filters relies on quantitative oxidation of iron nails (quantitative generation of HFO) in the large Fe^0 bed. The Fe^0 bed of the IITB filter corresponds to the Fe^0 unit of the KAF. Where one bed is not sufficient to lower the As concentration to acceptable levels (<10 $\mu g\ L^{-1}$), more Fe^0 beds in series are used [45]. On the contrary, KAFs contain some 5.0 kg of iron nails and are supposed to work for all raw waters. Clearly, where KAF was successful, the used 5 kg of iron nails was able to generate enough HFO for quantitative As removal. As a matter of fact, if different sources of iron nails are used to construct KAFs for the same location, it is likely that they exhibit differential As removal efficiency. This is exactly what is reported by Ogata et al. [3], but the rational is speculatively discussed. For example, Ogota et al. [3] assumed that the decreasing capacity of iron nails to quantitatively generate HFO would be restored if the content of the Fe^0 unit is replaced by new Fe^0 materials. However, the same authors reported that augmenting the amount of nails has not always improved the results. On the other hand, replacing the Fe^0 materials as suggested was independently performed by Mueller et al. [2], with less satisfactory results.

The conventional KAF is not really an appropriate technology as Ogata et al. [3] revealed that, after four years only 30% of 2833 KAFs distributed in Nepal were being used. In 74% of all cases, breakage or leaks were responsible for the non-use as the users were not able to repair the KAFs. The evidence that KAF is not efficient is discussed by Ogata et al. [3] and Mueller et al. [2] as a site-specific issue. In fact, the performance of the assessed designs of KAF for As removal was significantly influenced by the arsenic and iron concentrations of raw water. This argument would suggest that KAF efficiency depends on the local hydrogeochemistry, and thus appropriate KAFs for each water type should be designed. However, the argument based on the As/Fe ratio is not convincing as Fe^0 should be a source of dissolved Fe to mediate As removal by adsorption and co-precipitation [14]. The view that Fe^0 and its reaction products also mediate oxidation of non-charged As^{III} to negatively charged As^V is also present in the Fe^0 literature [6,23,46] but is not discussed herein. In the neutral pH range, negatively charged As^V is better adsorbed onto iron oxides and hydroxides [6]. According to Ogata et al. [3], the KAF type also play a significant role in the As removal performance, with concrete square type showing the best results. However, it should be kept in mind that the discussion started with the general low performance of KAFs for As removal [1–3,16,24,25]. The main research question is thus: Why is the conventional KAF not efficient? The answer in this communication is clear: Because of design mistakes highlighted. The next section summarizes the answer from the available literature on the Kanchan arsenic filters.

4. Rationalizing the Highly Variable as Removal Efficiency of KAFs

The previous section has already outlined some reasons for the high degree of variability of the As removal efficiency of KAFs as presented by Ogata et al. [3]. Mueller et al. [2] also observed such a high variability in efficiency and attributed it to: (1) the used iron nails, (2) the grain size of sand used, (3) the KAF design (plastic round, plastic square, and concrete square), (4) the ground water composition or hydrochemistry, and (5) the usage and mode of operation. Mueller et al. [2] reported on a "wide range of the overall removal efficiency" ranging from 5.81% to 97.1% for arsenic. Of the KAFs in used in the survey of Ogata et al. [3], up to 43% could not meet the national drinking water quality standards for arsenic (50 $\mu g\ L^{-1}$) and Escherichia coli (*E. coli*), respectively. This inconsistent and low As removal efficiencies reported in some cases raise serious public health concerns. Specifically, the widely held notion that the current KAFs is a universal technology for As removal may expose humans to As health risks when such filters fail to provide water meeting drinking water guidelines. Thus, the applicability of the KAF may need to be evaluated on a case-by-case basis, taking into account water hydrochemistry, operating conditions, and the design of the filter.

The documented high variability of As removal efficiency of KAFs was justified by considering the five main aspects, which are collectively either obvious or speculative:

(1) Geological background, for instance the correlation between As and Fe concentrations of the polluted groundwater. This is obvious; it should be possible to design efficient KAFs on a site-specific basis. That is, for instance KAFs for phosphate-rich waters or for highly As-polluted water. This is exactly what is done using the several IITB filters [45] at sites where one module is not enough. Another idea is to test more reactive Fe^0 materials like iron fillings or steel wool. However, these aspects have not been yet considered in Nepal as only iron nails are always used, and without characterizing the intrinsic reactivity. Available methods for characterizing the intrinsic reactivity of Fe^0 materials have been recently comparatively discussed by Lufingo et al. [47].

(2) Reactivity loss of iron nails and saturation of the sand bed. Both nails and sand are suggested to be changed regularly. For example, a yearly replacement of the sand bed was suggested [1]. This is also obvious as the sand bed captures colloids from the Fe^0 bed in a deep-bed filtration mode. The ITTB (Indian Institute of Technology Bombay) filter solves this issue by selecting the grain size of sand and using mostly gravel in the bed [45].

(3) The Fe^0 bed should be constantly wet but not immersed in water in order to promote the formation of HFO. This assertion is highly speculative as As is better trapped by colloidal iron hydroxides (Section 2). It also disproves the excellent results of Smith et al. [27] demonstrating that the BSF with embedded iron nails was more effective at removing As than the conventional KAF with nails in a diffuser basin above the BSF. Moreover, the authors of [27] rationalized the enhanced efficiency with increased contact time between water and nails and sustained corrosion. Mueller et al. [2] have not presented any in-depth investigations into this aspect and their conclusion disproved the century-old technology of coagulation which combines adsorption (onto aged HFO) and co-precipitation (with nascent HFO). Again in the Fe^0 bed of the IITB system [45], iron nails are completely immersed and the systems have been performing excellently for years. Clearly, complete immersion of iron nails is not likely to play any detrimental role in the performance of a KAF (Section 2). In contrast, it should produce more readily adsorptive colloids for As "collection" [27,31,45]. The As laden "flocs" are removed in sand filtration (straining) [45].

(4) Polluted water should be poured slowly and carefully in order to prevent displacement of the nails. Displacement of nails would create preferential flow and decrease the residence time of polluted water in the Fe^0 beds. This is obvious and easy to consider but its contribution to system failure can be considered as minor. Two reasons for this are that (1) considering this aspect has only slightly improved the performance of KAF [1,2],

and (2) the IITB filter even poured the water more vigorously and has not reported on any disadvantages [45]. Again, the Fe^0 bed should remove As (and other contaminants) by "flocculation" and the flocs are removed in the subsequent sand filters. This was the principle of the Anderson Process used at the Waterworks of Antwerp from 1883 on [4] and recently independently presented by many authors [44,48,49].

(5) Other KAF improvement activities include cleaning the whole system, adding calculated amounts of iron nails, completely replacing the iron nails, and using smaller iron nails. Collectively these actions did not improve the arsenic removal performance to the expected level [1–3,11]. For example, Mueller [1] added a sand layer above Fe^0 bed and reported an improved performance for 30 tested filters. However, the As concentration was rarely lower than the World Health Organiztaion (WHO)'s limit (<10 μg L^{-1}) for drinking water, and some filters still failed because of poor maintenance. This prompted the author [1] to recommend a better and regularly repeated instructions for the users. This recommendation attests that the conventional KAF is not really user-friendly, and thus fails to meet a key criterion for appropriate technologies. On the other hand, using a modified KAF design, Bretzler et al. [11] tested a Fe^0 bed made using very small iron nails, embedded between sand layers (initial [As] = 400–1350 μg L^{-1}) and reported on quantitative As removal (>90%). However, the effluent As concentrations were sometimes still above the WHO limits (<10 μg L^{-1}). The modifications by Bretzler et al. [11] depicted clearly better results than those of Mueller et al. [2] and Ogata et al. [3] (Figure 2). One option to further improve on the results of Bretzler et al. [11], and achieve water quality meeting the WHO limits is to use a series or treatment trains of Fe^0 filters. In principle, waters with complex hydrochemistry and high concentrations of As may require several treatment trains than simple and less concentrated waters [13].

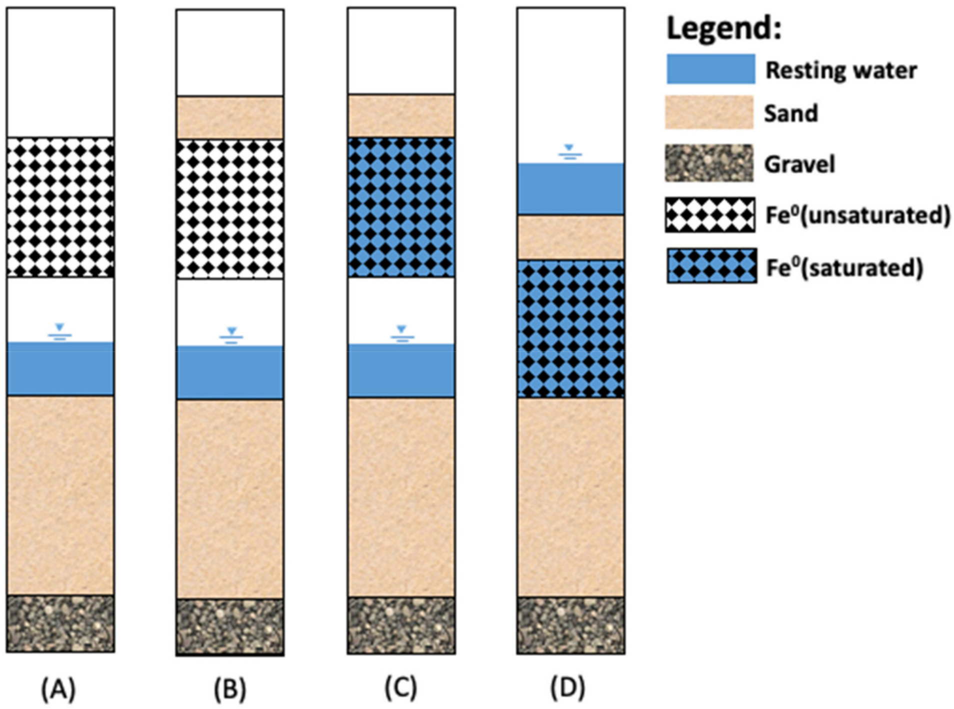

Figure 2. Diagram showing the set-up of the original Kanchan arsenic filter (KAF) and three different possible modifications. (**A**) represents the original KAF, (**B**,**C**) the modifications tested by Mueller [1,2], (**D**) represents one modification tested by Bretzler et al. [11] and Smith et al. [27].

5. Questioning the Suitability of KAF

In the current context of Nepal, it is important to verify whether people using KAFs are considered to have access to "improved" quality of water. The discussion herein is limited to As removal as it was the motivation behind developing the KAF (Fe^0-based filter). However, the discussion of the operating mode has suggested that conventional KAF devices should be less efficient in removing pathogens than conventional BSF (Sections 3 and 4). Therefore, in cases where well water is also polluted with pathogens, the utility and efficiency of the KAF is further reduced, rendering the technology almost useless. At this stage, a radical solution for Nepal can be going back to surface water or abandoning tube wells. In fact, conventional BSF and its proper amendment could guarantee the provision of safe drinking water in a decentralized and affordable manner [50–52]. Where there is no chemical contamination, solar pasteurization, or even water boiling alone will solve the problem [53–56].

The suggested improvement should be rapidly tested to assess whether KAF has a future at all. Prominent institutions are involved in the development of these filters (e.g., Eawag, Swiss Federal Institute of Aquatic Science and Technology in Switzerland or The University of Tokyo, Kashiwa in Japan), and hence could rapidly test the suggestions while systematically using instrumental analysis to monitor the efficiency. The government of Nepal and local universities and research institutions can also lead this research for the benefit of their own citizens. It is no longer acceptable that a technology that was introduced as emergency solution [22,23] has been used for 15 years without been proven efficient. This period corresponds exactly to the time-frame of achieving the United Nations Sustainable Development Goals (UN SDGs) (2016–2030), meaning that if the business-as-usual approach is maintained, Nepal and several other developing countries would not achieve universal access to safe drinking water by 2030 (Goal 6.1).

The improvements suggested herein correspond to at least two convergent calls: (i) recognizing Fe^0-based solutions as having a great potential for decentralized safe water supply in the coming decades [14], and (ii) the urgent need for a synthesis of available knowledge to accelerate the achievement of Goal 6 of the UN SDGs [57]. Our research group has already presented two synthesis paper in this perspective [58,59]. This short communication results from a multidisciplinary discussion, aiming to contribute to a paradigm of "leaving no one behind" without safe drinking water. The expected result is two-fold: (1) active researchers should be cautious and critical of the integrity of the literature research, and the technical soundness of information contained therein; and (2) local governments should lead the research agenda. The two main papers on which this communication is based [2,3] were led by foreign scientists from geographically distant areas. The question the arises, "Why could different authors collectively ignore warnings from the literature that conventional KAFs are not likely to be efficient" [24–27,35].

The idea of this communication is not to blame colleagues for their efforts to solve a long-lasting problem. Rather, their efforts in developing and improving the conventional KAF are acknowledged, and suggestions are made here to take advantage of the other aspects of the efforts started at the MIT—Massachusetts (USA) around the year 2000 to boost the proper dissemination of the improved KAFs and other frugal technologies worldwide.

6. Recommendations for More Efficient KAFs

Based on the findings that the large majority of conventional KAF are not functioning well (Section 4), and that evidence current improvement measures are not yet fruitful [2,3,11,26], the following key recommendations are made, which are consistent with other studies as summarized by Yang et al. [13] in this issue:

(1) To provide the households with long-term arsenic removal using Fe^0-based mitigation options, the original Kanchan design should be revisited. It seems that iron nails are not a suitable class of Fe^0 material for this purpose [11,26,27]. In fact, Bretzler et al. [11] tested small-size iron nails and the results are still not satisfactorily. On the other hand,

5 to 8 kg of nails are used in individual filters and the extent of their depletion is not yet addressed. It certainly makes sense to use less dense materials (e.g., iron coils, iron foam, scrap iron, and steel wool) to lower the extent of material wastage. In this regard, two very encouraging works are available: (a) Bradley et al. [51] used a steel wool having a diameter of 25 µm (grade 0000) and documented successful pathogen removal in a household filters before material depletion after six months; and (b) Tepong-Tsinde et al. [60] used a steel wool having a diameter of 50 µm (grade 0) and documented successful nitrate and pathogen removal in a household filter for 12 months, without any Fe^0 depletion. In other words, leaving iron nails behind in designing household Fe^0-based water filters seems to be the way forward in the design of the next generation KAFs.

(2) Testing both plastic and concrete KAFs in Nepal has revealed the very crucial importance of filter robustness for the continued use of the filter. Therefore, concrete versions of next generation Fe^0-based systems should be promoted;

(3) User's awareness on the value of good quality drinking water and the necessity to regularly monitor filter performance is very important in the promotion of KAFs as household filters. There are increasing calls for the equipping of analytical water laboratories everywhere, including in low-income countries [61–63].

(4) Critically evaluating available recent evidence on KAF is important for the improvement of the filters, this study demonstrates that more in-depth research is needed to uncover the huge potential of Fe^0-based filtration systems for drinking water supply at household level [64,65]. Given the crucial importance of the approach of a "synthesis of water research to achieve the Sustainable Development Goals by 2030" [57], this communication based on KAF is an important case study. The results should be disseminated beyond the scientific audience. Ideally, a coordinated strategy should be developed for the establishment of household Fe^0 filters, especially focusing on an analytical monitoring of the performance of the filters [13].

7. Conclusions and Outlook

This communication has presented the conventional Kanchan arsenic filter (KAF) for decentralized safe drinking water provision in rural Nepal and its limitations. Then three different paths to improve its efficiency are suggested. The first involves the addition of a gravel layer between the BSF and the Fe^0 unit and the immersion of the Fe^0 unit (Modification 1) (Figure 1). The second involves sandwiching the Fe^0 unit within the BSF (Modification 2) (Figure 2B). The third modification involves replacing iron nails with more reactive Fe^0 materials (e.g., iron fillings, scrap iron, and steel wool) (Modification 3). Modifications 2 and 3 have already been positively tested, but just in preliminary investigations [25,26,44], while the results of the IITB filters [45] suggest that Modification 1 combined with Modification 3 has the potential to operate satisfactorily. The discussion has also recalled which factors are important to consider when constructing a new improved KAF device: (1) Fe^0 intrinsic reactivity, (2) water flow velocity, and (3) user-friendliness and cost. The Fe^0 intrinsic reactivity has not yet received the attention it deserves, and should be the main focus of future investigations.

Whether or not the original KAF design is viable upon modification (Modification 1 combined with Modification 3) is still unclear [2,3,11]. Previous work available in the literature has shown that iron nails are not a suitable Fe^0 source [66,67]. The uncertainties in the HFO production kinetics are too large for predicting the behavior of KAF containing alternative Fe^0 sources like iron fillings or steel wool. Additional site-specific factors such as microbiological activities, varying water composition (e.g., PO_4^{3-}, SO_4^{2-}), and pH values will affect the performance of KAFs as correctly documented [2,3].

The following parameters primarily influence the efficiency of Fe^0-based filtration systems: (1) the grain sizes of Fe^0 and other aggregates (e.g., gravel and sand), (2) the intrinsic reactivity of used Fe^0, (3) the extent of water pollution (contaminant concentrations), (4) the water chemistry (e.g., pH value, Cl^-, PO_4^{3-}, SO_4^{2-}), (v) the filter bed expansion (e.g., depths of reactive layers), and (5) the ambient temperature. Until now too little attention was paid to the Fe^0 intrinsic reactivity. Future works must correct this approach. It should be kept in mind that raw water should be as most as possible be freed from physical contamination (e.g., suspended particles) for an optimal operation [13,66,67].

The present communication has given two interesting aspects. First, the original KAF design contains a conceptual mistake as the biological sand filter needs oxygen to operate properly. O_2 is however scavenged in the Fe^0 bed. Consequently, a conventional KAF removes all contaminants by adsorption and co-precipitation in the Fe^0 bed. Second, some recent improvement efforts would make KAF a maintenance-intensive design and probably not really applicable. However, the KAF concept is regarded as a cornerstone on which future small-scale technologies for safe drinking water provision will be developed. Thus, further work is required to address the limitations of the current KAF design.

Author Contributions: Conceptualization, C.N. and W.G.; methodology, Z.H.; formal analysis, Z.H., C.N., and W.G.; writing—original draft preparation, Z.H., C.N., and W.G.; writing—review and editing, E.L.N., V.C., Z.H., C.N., and W.G.; All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: Huichen Yang (Applied Geology, University of Göttingen) is thanked for technical support. We also would like to thank the peer reviewers for their valuable suggestions and comments on improving this paper. We acknowledge support by the German Research Foundation and the Open Access Publication Funds of the Göttingen University.

Conflicts of Interest: The authors declare no conflict of interest.

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