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Review

Kanchan Arsenic Filters for Household Water Treatment: Unsuitable or Unsustainable?

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Abstract: This article critically evaluates the conventional Kanchan Arsenic Filter (KAF) in order to determine the main reasons for its reported poor performance. The KAF was introduced in 2004 in Nepal and makes use of non-galvanized nails as a Fe^0 source for As removal. As early as 2009, the KAF was demonstrated to be ineffective for As removal in many cases. This was unambiguously attributed to the Fe^0 layer which is placed on top of a sand filter instead of being incorporated into a sand matrix. Despite this conceptual mistake, the conventional KAF has been largely distributed in Asia, and recent articles have assessed its sustainability. This study reiterates that the suitability of the technology, rather than its sustainability, should be addressed. Evidence shows that the KAF has the following design limitations: (i) uses iron nails of unknown reactivity, and (ii) operates on the principle of a wet/dry cycle. The latter causes a decrease in the corrosion rate of the used nails, thereby limiting the availability of the iron corrosion products which act as contaminant scavengers. Taken together, these results confirm the unsuitability of the conventional KAF. Besides correcting the design mistakes, more attention should be paid to the intrinsic reactivity of the used iron nails, including using alternative Fe^0 materials (e.g., iron filings, steel wool) for filters lasting for just 6 or 18 months. Specific design considerations to be addressed in the future are highlighted.

Keywords: arsenic removal; groundwater pollution; household water filter; public health; zero-valent iron

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1. Introduction

The population of the developing world, particularly in Africa and South East Asia has been suffering from diseases associated with poor drinking water supply for the past seven decades [1]. Lack of safe drinking water is a cause of infant mortality, poor health, reduced longevity, and low productivity [1–3]. Thus, providing safe drinking water has been recognized as a prerequisite for development [2,4]. During the past two decades, a myriad of technologies has been suggested to improve the availability of safe drinking water for domestic use (household level) [2,4]. The Kanchan Arsenic Filter (KAF) is one such household-level design which has the potential to support the efforts to meet universal safe drinking water supply by 2030 [5,6].

Household filtration systems for safe drinking water provision include slow sand filters [7–9], ceramic filters [10–12], filters containing bone char [13,14], filters containing biomaterials such as biochar [15–17], filters containing geomaterials such as laterite [18–20], and hybrid filters containing combination of materials [21–23]. The household slow sand filter is known as a biological sand filter (BSF) and has been successfully used in the developing world since the 1990s [8,24,25]. While conventional BSF designs address only microbial contamination, hybrid systems address chemical contamination as well, in a typical multi-barrier system [26–28]. KAF filters are such a multi-barrier system initially designed for the removal of arsenic and pathogens [29,30]. A KAF combines two proven affordable systems: (1) a slow sand filter (SSF or BSF), and (2) a metallic iron (Fe^0) based filter. The technical expertise for both systems is a century old [31,32]. Thus, upon proper design, a KAF should be one of the most efficient and affordable systems for safe drinking water provision at household level.

Kanchan Arsenic Filters were designed to address the arsenic crisis in South East Asia, where geogenic arsenic (As) pollution of natural water sources has long been a serious human health threat. The most affected countries include Nepal and Bangladesh [33,34]. In these countries, areas where As concentration in groundwater is below the World Health Organization (WHO) guideline value of 10 $\mu g\ L^{-1}$ in drinking water are scarce [5,6]. In Nepal, the severity of the problem was realized in 1999 after the first report published by Sharma [35]. However, to address the issue, it quickly became evident that with the limited financial resources in these areas, centralized water treatment options would be difficult to implement. As an alternative, decentralized water treatment systems applicable at a small scale (community scale, household level) were considered a good option. To date, efforts to find engineered point-of-use technologies for As removal are still ongoing and different types of materials, including nanomaterials [36], flax seed-based magnetic hybrid nanocomposites [37], magnetic composites [38], graphene oxide and its composites [39], iron oxide [40], and Fe^0 [29,30] have been tested. However, as proven in the early 2000s, Fe^0 remains the best material due to its capacity to remove a wide range of contaminants, including pathogens (e.g., bacteria, viruses) and toxic inorganic pollutants (e.g., U, F, As). In addition, Fe^0 is a cheap and readily available material locally [26,29,41–44]. The KAF, developed in 2002, was adopted based on these characteristics [29,30]. A KAF filter uses iron nails as a Fe^0 source for the in-situ production of hydrous ferric oxides (HFO) for As removal [29]. A project was launched in 2003 to promote the use of the KAF in rural Nepal, and over 24,000 units were in operation as of 2010, serving about 200,000 people. Besides monitoring campaigns, the performance of the disseminated KAF was not really evaluated until recently [5,6].

Evidence on the performance of the KAF in removing As is inconsistent. Table 1 summarizes important conclusions presented in the scientific literature regarding the performance of the KAF as independently evaluated over the years following its introduction.

Table 1. An overview of assessment studies and conclusions regarding the performance of the KAF presented in a chronological order. For the discussion herein, it will be important to consider two facts: (i) refs. [29,30] are from KAF research groups, and (ii) all the other reports are from independent studies.

Article	Number of Assessed KAFs	Duration	Performance Remarks
Ngai et al. [29]	1034	3 months to 1 year	Good
Ngai et al. [30]	1000	2 years	Good
Chiew et al. [45]	3	Almost 6 months	Poor
Singh et al. [46]	62	6 months	Poor
Ogata et al. [5]	2833	1 year	Poor
Mueller et al. [6]	38	2 years	Poor

The KAF was recommended and adopted in Nepal after four years of multiple laboratory and field investigations during which it was found to be the best technology for As removal [29,30]. Between 2004 and 2005, two blanket tests encompassing over 1000 of all the known types of KAFs were performed using technical and social criteria [30]. Ngai et al. [30] observed that, depending on the extent of As contamination (e.g., $\leq$500 µg L^{-1}), phosphate concentration ($\leq$2.0 mg L^{-1}), and the groundwater pH value ($\leq$8.0), the KAF could remove up to 90% of As. In contrast, Chiew et al. [45] assessed the KAF for almost six months in Cambodia using groundwater with As levels varying between 150 µg L^{-1} and 400 µg L^{-1}. In the same study, results showed that the KAF was inefficient, as As concentrations in the filtrate were rarely below the Cambodian standard (<50 µg L^{-1}). Singh et al. [46] made similar conclusions after having assessed 62 KAFs for the same duration in Nepal. Mueller et al. [6] extended their study to two years in Nepal and observed that just 7 out of the 38 tested KAFs could achieve the Nepali interim standard of 50 µg L^{-1}. Earlier, from 2014 to 2015, Ogata et al. [5] had conducted a vast monitoring campaign of 2833 KAFs in operation in Nepal and observed that just 30% of them were still being utilized, of which only 17% were capable of removing As to below the Nepali guideline. Taken together, the variability of these results attests to the inconsistent performance of the KAF, and thus raising questions about its reliability and suitability.

Therefore, there is a need to examine and ascertain the causes for the filter's poor and inconsistent performance reported in independent studies. A treatability performance assessment of the filter by the developers at the early stage of its introduction concluded that it was more ideal for specific geochemical conditions, specifically those with low As concentration and Fe-rich natural waters [29,30]. Independent studies have, however, revealed the variable performance of the filter even in the same geographic area, including those with the specified geochemical characteristics of low As and Fe-rich waters [5]. This suggests that the problem could be more intrinsic to the system design rather than just limited to the raw water geochemistry. Accordingly, a critical evaluation of the original design and its functionality is required to improve the filter's design, operation, and, hence, performance.

To date, three main flaws of the KAF have been identified: (i) low contact time, (ii) intermittent immersion of the used nails in the system which affects their reactivity, and (iii) O_2 depletion in the Fe^0 unit which impairs the functionality of the biosand unit [6,47]. In fact, the KAF has two compartments in its design layout: (i) a top diffuser basin holding iron nails (Fe^0 unit—which is the core of the system), and (ii) the bottom biosand unit, where biological decontaminantion is believed to mostly occur by virtue of a biofilm (*schmutzdecke*) supposedly formed on top of the sand bed (see schematic diagram in Section 3) [29,30]. Note that the development of the biofilm depends on the availability and concentration of O_2 in water. Despite earlier calls for improvement [46,48,49], the KAF has never been subjected to any notable design modification to enhance its performance [5,6,47,50]. In a recent review by our group [47], three different modifications were suggested to improve the KAF: (i) the replacement of iron nails by more reactive Fe^0 materials (e.g., steel wool, iron fillings, and scrap iron), (ii) the immersion of the Fe^0 unit, and (iii) the sandwiching the Fe^0 unit within the biosand unit. Out of these three modifications, the most viable, based on an established design principle, involved sandwiching the Fe^0 unit within the biosand filter [25,48,51,52]. With this modification, O_2 dissolved in water is directly made available for the development of the *schmutzdecke* which, in turn, improves the functionality of the biosand unit. Furthermore, a very limited quantity of O_2 accesses the incorporated Fe^0 unit. Under low O_2 concentrations, the filter's sustainability will be enhanced as less voluminous Fe^{III}/Fe^{II} oxides/hydroxides will be generated in the system [48,53,54]. However, evidence shows that the efficiency, particularly for As removal, rather than the sustainability of the KAF has been a concern since its introduction.

In the present article, the design and functionality of the KAF are critically evaluated in the light of the state-of-the-art knowledge on the remediation Fe^0/H_2O system. The present study builds on and extends some aspects of previous contributions by addressing the enigma associated with the KAF. The presentation starts with a description of the KAF. In addition, suggestions are made to improve the filter's performance. Then, a brief discussion of the main parameters affecting the proper operation of Fe^0-based filters is given, followed by a summary of the results of the filter's assessment studies. Finally, current design limitations, and future research directions are presented.

2. Materials and Methods

The search approach adopted in this study is based on a step-by-step process for selecting the literature in order to increase scientific credibility [55,56]. The focus was on the peer-reviewed literature on KAF. This is because the present review aims to offer a critical perspective. Note that the non-peer-reviewed grey literature were not included in this review. This is because the grey literature was observed to be written by authors with potential conflicts of interest, including (i) research groups working on KAF, and (ii) organisations responsible for developing and disseminating the KAF. Note that the KAF itself, as currently used, was the main object of this study. Because of this, many studies on As and/or As treatment using other non-KAF technologies were not considered.

2.1. Search Strategy and Selection Criteria

An automated search using Boolean techniques was conducted in three major scholarly databases, ISI Web of Science, Google Scholar, and Scopus, between October and November 2021. The search included studies published after the first appraisal of Fe^0 in household filters [33]. The search string combined the keywords: *water filter, Kanchan Arsenic Filter OR arsenic filter AND "Millennium Development Goals"* and their variants. The articles were exported and filtered in Microsoft Excel.

The search resulted in 40 publications: 5 in ISI Web of Science, 27 in Google Scholar, and 8 in Scopus. To refine the selection of the studies from the 40 papers, a criterion for inclusion was that only papers dealing with the KAF were then reviewed. These papers were mainly peer-reviewed research and review articles. The inclusion of review articles is premised on the assumption that they had certainly considered all the literature and other relevant information available at the time they were conducted. Out of the 40 initial articles, 8 met the inclusion criteria, of which 6 were research papers and 2 were review articles. Of the two review articles, one [47] was from our research group.

2.2. Completeness of the Literature

Table 2 presents the eight articles retrieved and used in this study. From Table 2, it can be seen that the six research articles which formed the basis for the present analysis were published between 2006 and 2021. It can also be seen that the available literature on KAF covers the period from 1999 to 2020. This corresponds to the period in which studies on the KAF were first published. Likewise, the literature on Fe^0 for water treatment in general is largely covered (1873–2020) [31,32,47]. It is assumed that the two research articles from SCOPUS by the KAF developers [29,30], which are, in essence, the same work, provide enough information on the research group's activities, including the filter's development, assessment, dissemination, and improvement. The extent to which they were considered by independent studies is also addressed. Taken together, this shows that all information pertaining to the KAF are likely to be contained in the selected papers used in this study.

Table 2. Some characteristics of the eight peer-reviewed articles on KAF found and used in this study. The extent to which the two papers from KAF research groups [29,30] were considered by the six other studies is presented, and indicated by the answer, 'Yes' or 'No', to the question of whether or not they were cited in these studies. 'N_T' is the total number of cited references. It can be seen that the entire period of existence of the Fe^0 remediation technology (130 years) is covered. Thus, the present review can be seen as complete.

Article	Type	Covered Period	N_T	Research Papers by KAF Developers	
				Ngai et al. [29]	Ngai et al. [30]
Chiew et al. [45]	Research	1981–2008	33	No	yes
Singh et al. [46]	Research	2001–2012	11	No	yes
Ogata et al. [5]	Research	1995–2019	19	No	yes
Mueller et al. [6]	Research	1995–2020	51	yes	yes
Tamalsina et al. [50]	Review	1927–2020	83	yes	yes
Huang et al. [47]	Review	1890–2020	67	yes	yes

3. The Kanchan^{TM} Arsenic Filter

The Kanchan Arsenic Filter (KAF) (Figure 1) is an award-winning household water filter that was developed in Nepal as a joint venture between the Massachusetts Institute of Technology (MIT—Cambridge, MA, USA), the Environment & Public Health Organization (ENPHO—Kathmandu/Nepal), and the Rural Water Supply and Sanitation Support Programme (RWSSSP) of Nepal [29]. The dissemination of the KAF started in 2004, following four years of multiple laboratory and field investigations within the framework of the MIT Nepal Water Project (NWP) [29,30]. The work identified and recommended the KAF in 2003 as the most appropriate technology to combat the As crisis in Nepal [29].

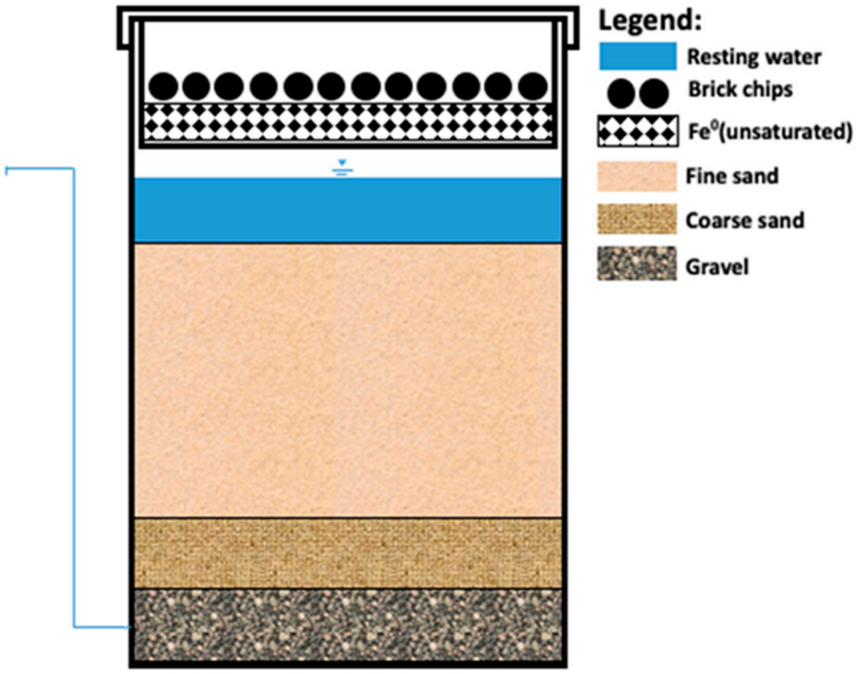

Figure 1. Schematic diagram of a Kanchan arsenic filter (KAF) showing its components (adapted from [30]).

The original KAF as presented by Ngai et al. [29,30] is built on the platform of a biosand filter (BSF) for intermittent household use and modified to include an As removal unit consisting of a diffuser basin containing non-galvanized iron nails (5 kg) as a source of Fe^0.

The stand-alone water filter can be manufactured by locally trained technicians with simple hand tools and using locally and readily available materials, including plastic containers, PVC pipes, non-galvanized iron nails, bricks, sand, and gravel. The design of the filter is said to have been considerably improved since its introduction, with optimizations made principally based on the local socio-economic conditions. The estimated cost of the KAF in Nepal as of January 2006 was US $ 19.

When water is filtered through the gravity-driven KAF, it first passes through the diffuser basin (Fe^0 unit) before reaching the biosand filtration (BSF) unit. While As is removed in the diffuser basin, pathogen removal mainly occurs in the BSF [29]. The Fe^0 unit also has the potential to remove pathogens [47]. Exfoliated Fe oxide-As colloidal particles from rusty iron nails are trapped in the BSF. There is an air space between the diffuser basin and the BSF unit in the filter. The KAF was principally designed to remove As and pathogens from water, even though iron, micro-pollutants, and turbidity can also be removed. Arsenic is removed by adsorption onto the surface of the rusty iron nails (i.e., hydrous ferric oxide—HFO) whilst pathogen (such as bacteria) removal mostly occurs either via physical straining provided by the fine sand layer in the BSF or by biological predation in the biofilm (*Schmutzdecke*) formed a few centimeters on top of the fine sand layer [29,30]. With a design filtration rate of 15 to 30 L h^{-1}, the KAF is reported to be capable of satisfying the daily drinking water needs of a family of 10 to 20 people according to the WHO recommendations of 7.5 L/person/day if the filter operates even only for 5 h per day [30]. The next section will recall the main factors affecting the proper operation of Fe^0-based filters, in general, before a summary of the results of the selected KAF assessment studies is presented.

4. Factors Affecting the Design and Operation of Fe^0-Based Filters

4.1. General Aspects

The evidence that Fe^0-based filters are effective decentralized water treatment systems has been widely published [26,28,57–61] and will not be discussed in detail here. Unfortunately, the available data have been achieved under various operating conditions, making even a simple comparison of independent research results extremely difficult. Here, it will suffice to emphasize that the system simply needs to be well-designed and in accordance with the water geochemistry at the point of use [25]. Knowledge on properly designing, assessing, and maintaining Fe^0-based filters has been continuously made available in the peer-reviewed literature since 2000 [33,45,62] and has been reviewed and updated by our research group since 2009 [25,28,48,63]. The main outcome of the synthesis of available investigations is that the proper design of Fe^0-based filters entails the proper consideration of some key design and operational parameters. For example, the quality of the used Fe^0 material alone could determine the good or poor performance of these filtering systems.

4.2. Relevant Design Considerations

There are six main factors affecting the design and operation of Fe^0-based filters: (i) Fe^0 intrinsic reactivity, (ii) the depth of the reactive zone, (iii) the proportion of Fe^0 within the reactive zone, (iv) the size and depth of the filter media (i.e., all aggregates including Fe^0), (v) the raw water quality (nature and extent of contamination), and (vi) the filtration rate, which is related to the hydraulic retention time. The water quality is not limited to the nature and extent of the contamination as each water body is, in reality, unique [24]. Rather, water quality includes many other water operational parameters (e.g., pH, electrical conductivity, interfering solutes, etc . . .) that are capable of influencing the performance of such filters. Such water quality parameters may affect the following: (i) the Fe^0 dissolution rate, (ii) the oxide scale at the surface of the pristine Fe^0 formation, (iii) the ionic conductivity of the formed oxide layer, and (iv) the oxide layer permeability [64–66]. It should be explicitly stated that Fe^0 oxidative dissolution is not instantaneous, and, in reality, each Fe^0 material has its own intrinsic reactivity. Likewise, the formation of Fe corrosion products (FeCPs) is a process that requires time, and the formation rate is not a constant function of time [67,68]. This signifies that a reliable Fe^0-based filter should simply be one in which the required treatment level is easily achieved within the bed for the selected filtration rate [24,42,48,58,69–73].

The evaluation of the performance of the filter should entail proper laboratory and field pilot tests [24,25]. This step is a prerequisite that should be conducted with the utmost care. The performance should be assessed by monitoring changes in the following parameters: (i) concentrations of relevant species, including contaminants and iron, (ii) hydraulic conductivity (permeability), (iii) pH value, and (vi) electrical conductivity [24]. The duration of the pilot test is also a crucial aspect to consider as it facilitates the identification of the design limitations and the determination of the frequency at which maintenance may be required. Ideally, the test should be stopped only after the total depletion of the used Fe^0 material, and replicated to account for different field situations. The resulting filter must be capable of being easily cleaned since its subsequent performance will largely depend on this, especially given that no filter is self-cleaning. It is only after conclusive and satisfactory results that the filter development and dissemination to the target population for drinking water treatment should be recommended.

5. KAF Assessments

This section gives an overview on KAF performance based on the six (6) research articles presented in Table 2 (Section 2.2). The presentation is limited to highlighting the filter's assessment approach, observations, conclusions, and/or recommendations of individual studies in the order of the publication date (Table 3). The key information from the review articles included for the present analysis, excluding ours [47], are also presented in Table 3. The analysis of the six research articles sought to address the following major questions: (i) Question 1: *'Has the KAF performance been satisfactory where distributed or evaluated?'* and (ii) Question 2: *'regardless of whether the response to Question 1 is "yes" or "no", did the authors explicitly (or even implicitly) indicate the need for design modification of the KAF?'* The KAF is, in fact, a filter which is still considered as innovative despite 18 years of existence. Several types of KAF, including the plastic round, plastic square, concrete round, concrete square, and fiberglass currently exist, as recently identified in Nepal by Ogata et al. [5]. The Gem505 version introduced in March 2004 is, for instance, a plastic round type [30]. The five different types primarily differ in the nature and form of the container. Whether this causes variability in performance or not is currently unclear and warrants further investigation.

Table 3. Overview of the papers reporting on KAF, excluding our own contribution [47], with particular attention to their answers with regard to questions 1 & 2. 'N°' is the identification number of each article, as used later in this review.

No.	Article	Some Key Observations	Comments
1	Ngai et al. [29]	The KAF performs satisfactorily, notably for the Terai region of Nepal type of groundwater. Cases of poor performance can only be due to improper filter construction and/or lack of maintenance.	This paper explains the development and describes the implementation process of the KAF in rural Nepal during the early days of its introduction. Question 1: Yes, Question 2: No
2	Ngai et al. [30]	The KAF is particularly suitable for natural waters that have the following characteristics: total arsenic ≤ 0.5 mg L^{-1}, phosphate ≤ 2 mg L^{-1} and pH ≤ 8.0.	Research article on technical and social evaluation of the KAF at pilot scale in Nepal. Question 1: Yes, Question 2: No
3	Chiew et al. [45]	The KAF was found to be inefficient, particularly for As removal in Cambodia. The filter's performance could be worse for MS2 coliphages (virus) removal than *E. coli* (bacteria).	KAF assessment at pilot scale in Cambodia. Question 1: No, Question 1: Yes

Table 3. *Cont.*

No.	Article	Some Key Observations	Comments
4	Singh et al. [46]	The KAF is inefficient and needs to be improved.	Pilot field assessment of KAF in the Nawalparasi District in Nepal. Question 1: No, Question 1: Yes
5	Ogata et al. [5]	They are currently more abandoned KAFs than those still in use in Nepal. Abandonments are mainly due to leaks, breakage and poor performances.	Mixture of literature review and field surveys on KAF in Nepal. Question 1: No, Question 1: Yes
6	Mueller et al. [6]	The KAF mostly performs well when influent water is initially highly Fe-rich. The filter needs design modifications (including increasing influent residence time and maintaining iron nails constantly immersed in the system) for performance improvement.	Mixture of literature review on KAF and an assessment study conducted in Nepal. Question 1: No, Question 1: Yes
7	Tamalsina et al. [50]	The KAF is particularly inefficient at treating As. Its performance could be improved by inserting an additional layer of human hair (which constituents have a high binding affinity for As(III) species) in the matrix of the filter's biosand filter unit.	Reviews KAF and makes suggestions to sustainably improve its performance. Question 1: No, Question 1: Yes

5.1. The Research Articles Co-Authored by Ngai

The two research articles co-authored by Ngai [29,30] describe the framework of the KAF design and give an extensive technical and social evaluation of it in the rural Terai region of Nepal. Ngai et al. [30] further develops or explains results already presented in Ngai et al. [29]. This includes results achieved under the following conditions: (i) within the course of the MIT NWP, and (ii) from two blanket tests encompassing over 1000 of all known KAFs performed between February to May 2004 and from November 2004 to February 2005 after the filter's introduction in Nepal in early 2004. How effective the KAF is at removing As and various other (chemical and biological) contaminants from water with iron nails through physicochemical processes that are mediated by iron ions generated in situ and subsequently formed (hydr)oxides is outlined. In particular, the reports show that average removal capacities of 85–90% As, 90–95% Fe, 80–85% phosphate, 85–99% total coliform, and 80–95% turbidity, and, with up to 0.35–0.40 units pH increase, could be achieved with the KAF if the raw water has the following characteristics: total arsenic $< 500\ \mu g\ L^{-1}$, phosphate $< 2\ mg\ L^{-1}$, and pH < 8.

Ngai et al. [30] stated that the "*KAF was found to be technically appropriate for the water conditions generally encountered in the Terai region of Nepal.*" The "*proper filter construction and installation and users' education to ensure proper performance*" were considered to be the sole outstanding problems with the filter [29]. This means that from a pure design perspective, the authors have considered the filter to present no flaw. In other words, independently, the six key design parameters presented in Section 4 were properly considered in designing the KAF according to the authors. However, no reference is made to the corrosion kinetics of the used iron nails.

Ngai et al. [29,30] have reported on the development, assessment and distribution activities of the KAF in Nepal. Their position favors an affirmative answer to Question 1 and a negative answer to Question 2. However, it is evident that the authors overlooked or neglected the impact of the random selection of iron nails on the performance of the filter. The two papers have nevertheless provided enough evidence that Fe^0-based filters are an effective decentralized water treatment technology.

5.2. The Research Article Co-Authored by Chiew

Chiew et al. [45] reports on a KAF assessment study that lasted nearly six months. The study was undertaken in Cambodia using three different natural As-contaminated well waters spiked with laboratory-cultured *E. coli* and male-specific coliphages (MS2 virus) to achieve a target concentration of 10^4 CFU/100 mL and 10^5 PFU/100 mL, respectively. The well waters initially had slightly different chemistries but were typical of the region (Preak Thum village, Kandal province). The measured parameters included: turbidity, conductivity, alkalinity, hardness, pH, dissolved oxygen (DO), nitrate (NO_3), chloride (Cl), total manganese (Mn), total sulfur (S), total phosphorous (P), total iron (Fe), and total arsenic (As). The initial As concentrations varied from about 150 μg L^{-1} to 400 μg L^{-1}, and were at least three times higher than the Cambodian standard (<50 μg L^{-1}).

Chiew et al. [45] summarized the results of their investigation with the following statement: "*The effectiveness of arsenic and pathogen removal was not constant over time, and was highly dependent on the influent composition. The filter was relatively ineffective in treating arsenic contaminated groundwater … The main reasons for poor arsenic removal was due to the combination of high influent P (>0.5 mg L^{-1}) and low Fe (<5 mg L^{-1}) concentrations … the added iron nails were largely ineffective due to insufficient contact time with the water.*"

The statement from the authors is clear: the KAF is ineffective, and the problems are three-fold: (i) raw water quality, (ii) iron nails' reactivity (insufficient in many cases), and (iii) the filter's filtration rate (said to be too high). Clearly, based on the conclusions of the authors, three of the six factors presented in Section 4 were not properly considered. It should be noted that the natural water used for this study had As levels within the range recommended by Ngai et al. [30]. Yet, the filtrate As concentrations (varying between 74 and 226 μg L^{-1}) remained above the Cambodian drinking water standard. It, therefore, likely that the iron nails' ineffectiveness was mostly due to a low reactivity. In other words, solely attributing it to insufficient contact time can be considered a mistake.

Based on this presentation, Chiew et al. [45] have negatively and positively answered to Question 1 and Question 2, respectively. The authors made two major recommendations to improve the filter's performance: (i) reduce its filtration rate, and (ii) ensure the constant immersion of the nails in the diffuser. The work has shown that effective As treatment with this device is also highly dependent on the initial Fe concentration in the natural water.

5.3. The Research Article Co-Authored by Singh

Singh et al. [46] reports on KAF assessment against treatability performance for 62 randomly selected household groundwater tube wells in the Nawalparasi district (Nepal) for over 6 months. The tube well waters were highly As-affected, such that 41 had initial As concentrations above the Nepali drinking water quality standard (50 μg L^{-1}). The assessment herein is limited to KAF As treatability efficiency. Apart from the As initial concentration (mean and median value: 133.33 and 74 μg L^{-1}), no other specific information was given on the qualities of the influent waters nor on the used iron nails and their characteristics.

The following statement summarizes the results of the study: "*Assessment of influent and effluent water samples from 62 households showed that only 54 % of KAFs reduced the elevated arsenic concentration to less than 50 μg/L. The effectiveness was even lower when tested against the WHO standard.*" The authors added that: "*we did not find significantly high efficacy of KAFs in reducing unsafe influent arsenic level to the safe level under the in-situ field conditions.*" The study does not explicitly nor implicitly identify any cause for the reported poor performance. However, it recommends that the KAF be redesigned or improved, but without providing any details on what to modify. Singh et al. [46] have, therefore, negatively answered Question 1 and affirmatively answered Question 2.

5.4. The Research Article Co-Authored by Ogata

Ogata et al. [5] is the largest field survey of KAFs in operation, performed in the Nawalparasi district (Nepal) from 2014 to 2015 and covering 2833 KAFs with usage periods varying from 2 months to 10 years. The presentation starts by a brief literature review on using KAF in Nepal, followed by the results of the investigation. The results confirm the conclusions of Chiew et al. [45] and Singh et al. [46].

The authors reveal that a large number of the KAFs distributed in Nepal starting from 2004 are not being (or have not been) used, and their owners have simply preferred to return to drinking untreated As-contaminated water. Specifically, of the 2833 filters, 1283 were found to have been abandoned, whilst just 30% of the rest were still being utilized. The abandonment is said to have been mostly caused by breakage or leakages, while 87% and 57% of the 30% still-in-use filters could meet the drinking water standards for As and *E. coli*, respectively. Another important aspect of the study by Ogata et al. [5] is that it has used regression analysis to comprehensively demonstrate that: (i) KAFs perform variably even in the same geographic area, (ii) KAF usage status generally decline 4 years after installation, and (iii) the KAF performance is particularly influenced by certain parameters, including influent As and Fe concentrations, KAF type, and use frequency. The conclusions of the study are better captured by the following statement: *"The KAF arsenic removal amount was significantly influenced by the arsenic and iron concentrations of influent water and KAF type... Long-term use of KAFs (more than 4 years) was assumed to be a cause of the decreasing capacity of iron nails to supply ferric hydroxide to influent water, which led to decreased arsenic removal capacity."* However, the question of the intrinsic reactivity of the nails was not explicitly raised, and it was possibly unknown.

Ogata et al. [5] favour a negative answer to Question 1 and a positive answer to Question 2. The authors suggested two main measures to improve the performance of the filter, including: (i) fixing the filter's filtration rate with respect to its capacity and the nature of influent water, and (ii) frequently replacing the nails in the system. No replacement frequency is suggested, but it is indicated that it does not necessarily have to be on the basis of a 3-year cycle, as recommended by Ngai et al. [30]. Ogata et al. [5] have also suggested that, with the KAF, microbiologically contaminated natural water sources should be avoided. This was based on the poor removal of *E. coli* by KAF.

5.5. The Research Articles Co-Authored by Mueller

The three research articles co-authored by Mueller report on KAF assessment [6] and some original investigations by the authors to improve the filter's As removal capacity in the lowlands of Nepal (Terai region) [74,75]. Mueller et al. [6] evaluated 38 selected KAFs for which poor performance for As removal has been reported for 2 years in order to determine the reasons for the reported limited performance and define improvement measures. They used water samples collected from 38 randomly chosen wells from the ENPHO database of wells where filtered water exceeded the Nepali drinking water standard in previous measurements.

Mueller et al. [6] stated that: "*only 2 of the 38 selected filters were capable of removing As to below the WHO guideline of 10 μg L^{-1}, and only 7 of the 38 filters reached the Nepali interim standard of 50 μg L^{-1}*". As for the reasons for the ineffectiveness, they wrote that: "*The most relevant factors were the concentrations of As and Fe in the raw water, with the best removal efficiency observed for water with low As (123 μg L^{-1}) and high Fe (5.0 mg L^{-1}). Although the concentrations of other elements, pH, flow rates, and contact time with ZVI also played a role, the combined evidence indicated that the reactivity of the frequently drying nail beds between filtrations was insufficient for efficient As-removal.*"

The work has indicated more than four of the influencing factors presented in Section 4 but missed the intrinsic reactivity of used nails. Nevertheless, the authors suggested raising water outlets with flow restrictions to keep nails permanently immersed and to increase contact times as measures of improvement. Meanwhile, the first step of their subsequent project, which aimed to optimize KAF adapted in the lowlands of Nepal, focused on testing the region's groundwater composition. However, on-site filter handling has not yet really succeeded in clearly defining the operational geochemical conditions limiting

As removal [74,75]. Mueller and co-workers [6] have negatively answered Question 1, but affirmatively answered Question 2.

5.6. Critical Evaluation

Table 4 summarizes the results and the operational conditions of the above-presented six studies. It shows, in particular, that there is a high degree of variability in the filter's performance. The best performances were reported by the KAF research groups [29,30]. An interesting point is that all independent studies have globally reported on a relatively poor performance, even under the "ideal" geochemical conditions (total arsenic $\leq$ 0.5 mg L^{-1}, phosphate $\leq$ 2 mg L^{-1}, and pH $\leq$ 8), defined by Ngai et al. [29,30]. The logical conclusion which could be derived from this observation is understandable. However, from a pure analytical perspective, this suggests that, besides the variable filtration rate, the obvious discrepancies between studies (Table 3) may be due to an internally unsteady parameter (the nails' corrosion kinetics). It should be noted that these studies globally reveal that iron nails have been employed in these filters without being characterized, and no effort has been undertaken to correct this design mistake, despite the availability of testing methods in the scientific literature for decades [76–79]. Overall, the results in Table 4 support comments from Table 3 that: (i) the KAF does not always guarantee good filtered water quality (Question 1), and (ii) the KAF needs design modifications for performance improvement (Question 2).

Table 4. Summary of the operational conditions and results from the six KAF assessment studies presented in Table 3. Articles are represented by their numbers as indicated in Table 3. "n.s." stand for "not specified".

Article	Influent Water Parameters						
	pH Value	**[As] (µg L^{-1})**	**[Fe] (mg L^{-1})**	**[P] (mg L^{-1})**	**Hardness (mg/L)**	**Number of Tested KAFs**	**Location**
1	<8	<500	n.s.	<2	n.s.	1034	Terai/Nepal
2	7.18–7.26	<10–1000	0.1–10	0.23	n.s.	1000	Terai/Nepal
3	7.5 ± 0.2	150–400	<5	>0.5	n.s.	3	Cambodia
4	n.s.	133.13	n.s.	n.s.	n.s.	62	Newalparasi/Nepal
5	6.0–7.5	0–1320	0–10.0	0–1	36–3687	2833	Newalparasi/Nepal
6	7.04–7.81	95.5–798.7	0.51–5.91	0.12	n.s.	38	Terai/Nepal
	KAF design specifications						
	KAF type	**Filter's height (cm)**	**Fe^0 unit's height (cm)**	**BSF's height (cm)**	**Fe^0 Type**	**Fe^0 (kg)**	**Flow rate (L h^{-1})**
1	1 (plastic round)	49.6 *	14.5 *	28.1 *	Nails	5 *	n.s.
2	1 (plastic round)	49.6 *	14.5 *	28.1 *	Nails	5 *	15–25
3	1 (concrete square)	91	25	54	Nails	5	n.s. (but contact time ~3 min)
4	n.s.	n.s.	n.s.	n.s.	Nails	n.s.	n.s.
5	5 (all the types)	49.6–91.0	14.5–25.0	28.1–56.0	Nails	5	n.s.
6	n.s.	n.s.	n.s.	n.s.	Nails	4.05–5.2	n.s.
	Effluent water parameters & investigation duration						
	pH	**[Fe] (mg L^{-1})**	**[P] (mg L^{-1})**	**[As] (µg L^{-1})**	**Removed As (%)**	**Duration (year)**	
1	n.s.	n.s.	n.s.	n.s.	>95	0.25 to 1	
2	7.55–7.63	<0.1–3	0.036	≤50	85–90	2	
3	7.9 ± 0.1	<0.05	n.s.	74–226	39.4–74.9	~ 0.5	
4	n.s.	n.s.	n.s.	56.45	<50	0.5	
5	6.0–7.5	0–5.0	0–2	0–590	0–100	1	
6	n.s.	n.s.	n.s.	n.s.	6.28–98.5	2	

Note: * Data from Ogata et al. [5] for the dimensions of plastic round KAF type.

In a recent review, Tamalsina et al. [50] suggested an innovative way to increase the As removal capacity of the KAF. This entails the insertion of a human hair layer into the BSF unit. Human hair was said to be "*rich in fibrous keratin proteins containing cysteine which has a sulfhydryl group of a high binding affinity for As(III) species*". The effectiveness of this modification has not yet been experimentally verified, but if such an idea was to be put into practice, it would certainly require that the bed be thick. However, incorporating a pure thick layer of human hair into the sand matrix could induce a great decrease in the original system's initial porosity and a quick loss in permeability. The occurrence of the filter's clogging should even be expected at the early stage of its use. Consequently, it is still believed that the KAF will remain unviable upon such a modification. The use of human hair in drinking water filtration systems may also raise cultural and ethical concerns. Tamalsina et al. [50] also envisaged the integration of two KAFs in series, but its implementation would be quite difficult. The main constraint, as also realized by the authors, is that this will, in reality, result in twice the cost of installation and maintenance of the KAF.

It should be clearly stated that the idea behind the present evaluation is not to downplay the efforts of some colleagues. Rather, their efforts are acknowledged, and the present study takes advantage of the convincing and acceptable aspects of their various contributions to further suggest ways to solve the problems associated with the KAF.

6. KAF Design Mistakes and a Path to Improvement

The presentation to this point has shown the ineffectiveness of the KAF, and that very little attention has been paid to independent reports demonstrating this. Chiew et al. [45] even went so far as to make it clear that people depending on a KAF to provide them with clean drinking water are in no way safe from As contamination. The present study does not, therefore, simply seek to review the KAF, as this has already been undertaken in recent related reviews [47,50], but to insist on the need for a re-design based on evidence demonstrating its inefficiency arising from the fact that the KAF was effectively conceived with some mistakes.

The factors that have been identified as negatively affecting the performance of the KAF in previous studies (see Section 5) can be summarized in six points:

(i) The raw water quality: the prohibitive geochemical conditions have not yet been clearly defined as most of unsatisfactory results were even observed in conditions close to the "ideal" defined by Ngai et al. [30];
(ii) The contact time: the current filtration rate (varying from 15 to 30 L h^{-1}) is said to be too high and, hence, does not allow enough reaction time between contaminant scavengers (FeCPs) generated in situ and contaminants;
(iii) The wet/dry cycle principle on which the filter operates: the intermittent immersion of the nails in the system causes a progressive decrease in their reactivity with time;
(iv) The iron nails' ineffectiveness in several cases to generate sufficient FeCPs for As and other contaminants' collection: this was wrongly attributed solely to the limited contact time or nails' reactivity loss resulting from their non-permanent immersion in the system;
(v) O_2 depletion in the Fe^0 unit: this was proven to disturb the operation and functionality of the biosand unit;
(vi) The long-term use of the filter without an established frequency for regular/periodic maintenance.

Another aspect is that the difference between the different types of KAFs is not limited to the nature and form of the container but includes the size and depth of the filter media [5]. This has been proven to also contribute to the variability globally observed in the performance of the filter. In particular, Ogata et al. [5] observed that the concrete type was the highest performing and most durable of all the existing types, thereby demonstrating the importance of the robustness. However, the present study reiterates that the main problem of the KAF is the use of poorly characterized iron nails of unknown reactivity

(Problem 1). This is in addition to the wet/dry cycle principle on which the filter operates (Problem 2). The next section will discuss this in further detail. Note that the reaction kinetics (corrosion rates) for the iron nails used in the conventional KAF are not determined. This implies that its theoretical breakthrough point is, in fact, unknown. In other words, it is not possible to determine when Fe^0 will be exhausted, and thus, to determine time intervals between maintenance. In the absence of this key information, independent assessment results, even those obtained under similar experimental conditions, are not really comparable. Likewise, an economic analysis, including maintenance, replacement, and lifetime costs, is not possible.

6.1. Specifications on the Main KAF Design Limitations

A KAF is reported to work under the principle of two proven water treatment techniques: (i) As adsorption onto FeCPs in the diffuser basin (holding iron nails), and (ii) pathogen removal in the subsequent slow sand filtration [29]. The extent of As removal in the diffuser basin in essence depends on the availability of FeCPs as the adsorption process itself is rapid. This means that the intrinsic reactivity of used iron nails is really a key design parameter. The present review has insisted on the extent to which this parameter has been considered in designing and assessing KAFs. The most obvious limitation of the KAF design is that reactive nails consume dissolved oxygen (O_2) essential for the formation of the *Schmutzdecke*, which, in turn, is critical for pathogen removal in a conventional BSF [25,48]. In other words, in a well-operating KAF, there is limited to no pathogen removal. Pathogen removal also occurs through the following processes: (i) adsorption and co-precipitation in the diffuser basin, and (ii) adsorption onto the subsequent coated sand. Sand is coated by FeCPs from the diffuser basin. This presentation suggests that even a well-designed KAF can be worse than a BSF (absence of the *Schmutzdecke*) for pathogen removal while As removal depends on the intrinsic reactivity of used iron nails.

The original KAF operates on a wet and dry cycle principle which, in other words, allows nails in the diffuser to dry between filtration events. This, basically, can generate two functional problems. The first is that the formed oxide scale at the surface of pristine Fe^0 becomes dehydrated and firmly adheres at the material surface, thereby reducing the permeability of the scale. The inability of water to easily access a pristine Fe^0 surface slows the corrosion process, such that, irrespective of the used Fe^0 reactivity and the nature of the influent water, the availability of FeCPs may be progressively reduced to the extent of becoming insufficient for the fixed filtration rate [80]. The second problem is less serious, but its underestimation would be a great fallacy. It has to do with the inability of the residual water remaining in the filter to further get enriched with Fe until the next filtration event. The strong dependence of the KAF performance for As removal upon the influent initial Fe concentration is well-demonstrated in the literature [5,6,30]. This means that for influents with initial low Fe concentrations, a system allowing the residual water remaining in the filter to be continuously enriched with Fe could have permitted an instant compensation and hence helped meet the required treatment level given the limited contact time characterizing the original design [45,75]. Another issue with this wet and dry operation principle which is more likely to occur in saline environments is the acceleration of the corrosion process due to high salinity [48,81]. In fact, with increased salt concentration in the vicinity of Fe^0 during dry periods favoring an acceleration of O_2 transport across the oxide scale shielding the Fe^0 surface, the formation of Fe hydroxides is progressively and continuously delayed during wet periods. However, such an effect is less expected with the groundwater from the lowlands of Nepal.

Taken together, this demonstrates that the KAF was unintentionally designed with inherent errors predisposing it to failure. Fortunately, an increasing body of evidence now exists on how to address these design limitations and improve the performance of the filter.

6.2. Design Amendments for Effective Improvement

The effective path to solving the enigmas associated with the KAF should primarily seek to address the two above-mentioned fundamental problems. Their proper consideration integrates almost all the flaws presented (in points) in Section 6. For instance, the issue raised in point (iv) is an expansion of Problem 1. Correctly solving Problem 1 by selecting iron nails on the basis of their corrosion rates (intrinsic reactivity) takes the raw water quality (point (i)) into account. In fact, the determination of the suitable Fe^0 material to use as a filter medium in a specific site is undertaken in accordance with the geochemistry of the area's main natural water sources (including water from boreholes and springs, surface water, and shallow groundwater) [68,77–79]. Furthermore, as already described, with a known intrinsic reactivity, the establishment of the time intervals between maintenance (resolution of point (vi)) is possible.

There are currently at least four available tools to characterize the intrinsic reactivity of Fe^0 materials: (i) H_2 evolution [76,79], (ii) Fe^0 dissolution in EDTA (EDTA method) [77], (iii) discoloration of a methylene blue solution by Fe^0 [82–84], and (iv) Fe^0 dissolution in 1,10-Phenanthroline (Phen method) [78]. Two of them (the EDTA and Phen methods) have the particularity to be based each on a parameter (k_{EDTA} and k_{Phen} respectively) which could enable their purposeful selection. However, none has yet been standardized, but the suitability of various types of Fe^0 materials (e.g., scrap iron and steel wool) for water treatment was established/confirmed using the EDTA method [67,68,77,78,85]. This suggests that it could be successfully applied for iron nails' selection, as proven by the pioneering works of Hu et al. [67]. For example, if it is established that, in a given region, the usable iron nails have to exhibit a k_{EDTA} value above a critical value, the remaining task will be to determine this critical value. For instance, for Sout East Asian countries with groundwater characteristics similar to those of Bangladesh, the k_{EDTA} value of Hussam and Munir [26]'s SONO arsenic filter composite iron matrix (CIM) could be used as an initial guide.

There is currently a growing body of research even seeming to prove that iron nails would not be a suitable class of Fe^0 material for use in household filters [44,47,49,86,87]. This is because: (i) a huge quantity (5 and 8 Kg) is generally required in individual filters, (ii) unsatisfactory results have been reported even with smaller sizes [44], and (iii) the extent of the materials' depletion is not yet addressed. This suggests that the use of alternative Fe^0 materials should also be considered. Cheap and less dense Fe^0 materials such as scrap iron, iron coils, iron foam, and steel wool which already have a known extent of exhaustion could potentially be applied as alternatives to iron nails in KAFs. Moreover, they could aid to lower the extent of material wastage. Steel wool, in particular, has already been positively tested for the removal of pathogen and chemical contaminants in household filters for a year without Fe^0 exhaustion [27,28].

Figure 2 depicts a modification of the conventional KAF which would certainly enhance its efficiency because the Fe^0 unit is completely immersed (solving Problem 2) and provided that Problem 1 is properly considered. Problem 2 corresponds to the above-mentioned wet/dry cycle principle (point iii) on which the original filter operates. The Fe^0 unit is completely immersed by raising the outlet tap to above the level of the nail bed in the diffuser basin. The gap between the diffuser and the fine sand layer is filled with a gravel layer. The filtration rate (point (ii)) is a parameter which should be fixed accordingly. An additional interesting aspect of these modifications is that the risk of a preferential flow creation, also contributing to decrease in contact time between contaminated water and contaminant collectors in the diffuser, most likely occurring with the original KAF as a result of nails' displacement in the diffuser during raw water introduction in the filter, would be almost fully prevented.

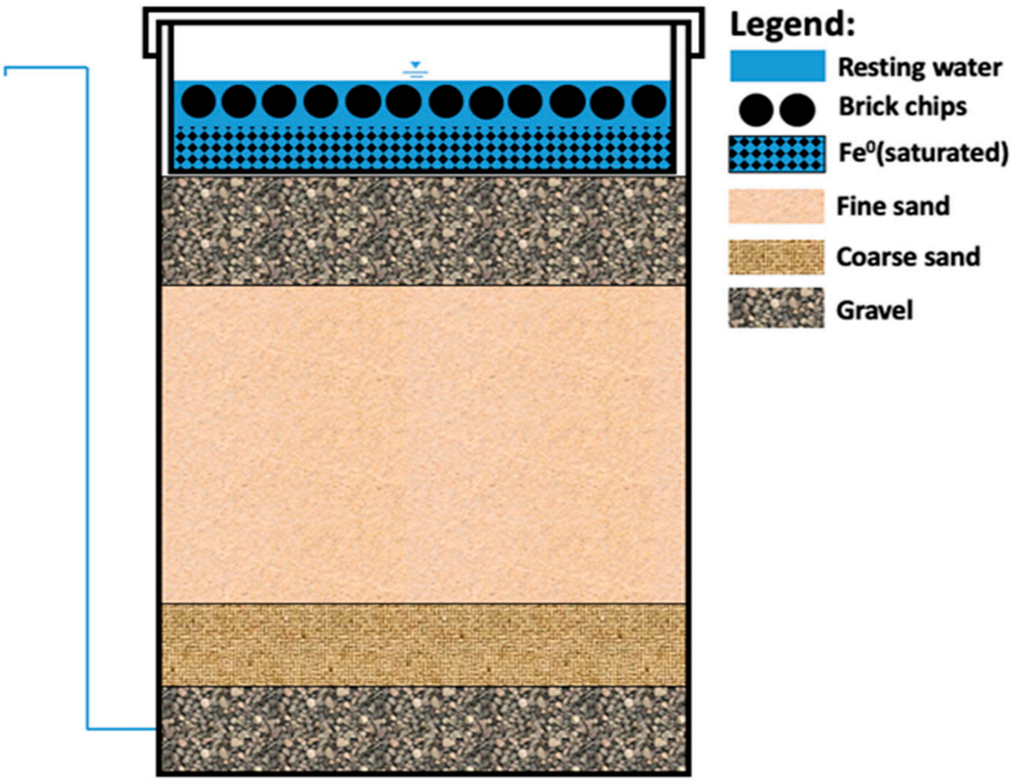

Figure 2. Diagram of a modified version of the original KAF to immerse the Fe^0 unit showing its components (modified after [30]). The total immersion of the Fe^0 unit is rendered possible by raising the outlet tap to above the level of the nail bed in the diffuser.

It should be noted that with the present modifications, the Fe^0 unit is still expected to disturb the operation and functionality of the biosand unit. In other words, Figure 2 does not address the problem raised in point (v). The only way to avoid O_2 depletion by the Fe^0 unit and render it available for the *Schmutzdecke* development is to insert the Fe^0 layer into the biosand filter's matrix [47,48,51]. This arrangement has also been proven to enhance the sustainability of Fe^0-based filters by creating low O_2 conditions. Under low O_2 conditions, less voluminous Fe^{III}/Fe^{II} oxides/hydroxides are generated [53,54]. However, permeability loss has not been reported with the KAF, and evidence shows that it is unlikely to occur as a result of the volumetric expansion of FeCPs, thereby making the question of sustainability less of a concern. The discussion herein is limited to the efficiency, particularly for As removal, as it was the main motivation behind developing the KAF. The discussion of the operating mode has suggested that, even after the above modifications, the KAF will still be less efficient in removing pathogens than conventional biosand filters. Therefore, it is emphasized that the resulting filter, as presented in this section, would be more adapted for groundwaters not too biologically polluted.

6.3. Maintenance and Quality Control

The present review has confirmed the need to revisit the KAF to provide households with long-term, Fe^0-based arsenic removal filters. A comparative study of the different kinds of KAF in Nepal has already shown the importance of the filter's robustness [5], thereby suggesting that, besides the consideration of the above-suggested improvement measures, the concrete version of the filter should be promoted for its continued use. Equally, users' awareness on the necessity to regularly monitor the filter's performance by controlling the drinking water quality is very important. Accordingly, a prerequisite would be to install equipped (and accredited) analytical laboratories and make them accessible in areas of concern. There are even increasing calls for the equipping of analytical water laboratories everywhere, including in low-income countries [42,47,88–92]. Based on analytical results, there are three options: (i) continue using the filter as far as the filtered water quality remains good; (ii) abandon it when its performance drops because of lack of maintenance, and (iii) clean it immediately when the analytical results suggest so.

7. Conclusions

This review explicitly argued that the KAF, commonly used in most households of South East Asian countries to produce drinking water, was designed with some mistakes responsible for the reported poor performance. None of the six research articles on which the present study is based reported any problems related to the filter's sustainability. Rather, all four papers from independent assessment studies and the two included review articles provided enough evidence proving its inefficiency. By evaluating the filter's design and functionality through available performance assessment studies and in the light of state-of-the-art knowledge on the remediation Fe/H_2O system, the present study intended to ascertain its main design flaws and, thereby, the key modifications required to achieve performance improvement. The main identified problems are that: (i) the KAF makes use of poorly characterized iron nails and of unknown reactivity as the Fe^0 source, and (ii) the KAF operates on a wet/dry cycle principle. This random selection of used iron nails has been the central rationale for observed variability in the filter's performance, while its operating principle favors a continuous decrease of the material's reactivity in the system. A proper selection should be based on the material's intrinsic reactivity and undertaken with respect to the geochemical conditions in the target area of application. Applicable tools to achieve this, including the EDTA method [77] have been suggested. It is also suggested that the use of alternative, cheap and less dense Fe^0 materials which already have a known extent of exhaustion (e.g., scrap iron and steel wool) be envisaged. Finally, a modified design of the KAF where the outlet tap is raised above the Fe^0 bed in the diffuser to ensure the Fe^0 material's constant immersion was presented.

Overall, the present study has clearly demonstrated that more in-depth research is necessary to improve KAF performance, and, by extension, to harness the enormous potential of household Fe^0-based filtration systems for safe drinking water provision. Given that the general suitability of Fe^0 materials for water treatment is well-established [80,93], and considering the success of the Institute of Technology, Bombay (ITTB) filter [43,94], it is envisaged that, upon considering the suggestions made herein, a satisfactorily performing KAF adapted for specific sites as influenced by As speciation and the presence of co-anions (e.g., $PO_4{}^{3-}$, $HCO_3{}^{-}$, $SO_4{}^{2-}$, Cl^-, etc.) will be found.

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