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Effectiveness, user acceptability and sustainability of Arsiron Nilogon: a rural technology for arsenic removal from drinking water†

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An investigation of groundwater of Kuruabahi village in the Golaghat district of Assam, one of the worst arsenic-affected states in India, revealed a widespread contamination of arsenic up to 344 μg L^{-1}, much above the WHO guideline value of 10 μg L^{-1} for drinking water. Except a few, most of the villagers were unaware of its connection with prevalent cancer and other arsenicosis symptoms in the village. This study examines the experience of implementation of Arsiron Nilogon, a rural technology, for removal of arsenic at all 320 households in the village. Water samples from all groundwater sources (tube wells) were tested for arsenic and other heavy metals using an atomic absorption spectrophotometer (AAS) attached to a hydride vapor generator (HVG) and for other water quality parameters by standard methods. The arsenic concentrations in all 320 treated water samples have been found to be undetectable (<2 μg L^{-1}) using an AAS-HVG, along with other relevant water quality parameters including heavy metals conforming to the WHO guidelines during periodic testing, which confirm the very good technical performance of the Arsiron Nilogon method in the field. The pH of all water samples was between 6.32 and 7.13 initially, which increased to 7.3 after treatment. The increase of the pH between 7.0 and 7.3 after treatment may be correlated to recovery from the chronic acidity problem after they started use of the filters, as reported by some villagers, an additional benefit of the filter. The safe tiny solid sludge was collected by all users as advised for proper disposal. The overall percentage of uninterrupted users two years postimplementation was found to be 70.63%, which endorse the good user acceptability of the filters.

Sustainability spotlight

Arsenic exposure through contaminated groundwater poses a significant risk to public health worldwide. The arsenic hotspots span across Asia, America, and Europe. Access to arsenic-free water remains a key challenge, especially for the population of remote and rural areas. This study examines the performance of a rural technology that is highly efficient, of extremely low-cost, easy to use, safe, and environment-friendly giving it distinct advantages compared to other existing options for the purpose. Its adoption in the chosen habitations presents itself as a viable and sustainable option for implementation in other rural communities facing the menace of arsenic to meet the UN sustainable development goals: clean water and sanitation (SDG 6) and good health and wellbeing (SDG 3).

1. Introduction

Among the available sources of drinking water, groundwater serves as a vital resource for the survival of humanity and the ecosystem. Groundwater accounts for more than 60% of irrigation water and 85% of rural drinking supplies in India.[1] Although less susceptible to microbial contamination compared to surface water, the presence of various natural or geogenic and chemical contaminants is often encountered in groundwater. One such natural inorganic contaminant having adverse human effects is arsenic.

Arsenic, a toxic groundwater contaminant inflicts serious threat to human health and has become a worldwide concern today. Its prolonged consumption causes arsenicosis of various types and is considered as a potential carcinogen.[2–4] It is also associated with cardiovascular diseases and diabetes, linked to negative impacts on cognitive development and increased deaths in young adults.[5,6] According to the World Health Organisation (WHO), about 140 million people worldwide consume drinking water contaminated with deadly toxic arsenic higher than the prescribed provisional guideline value

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of 10 μg L^{-1} set by the WHO.[7] Countries like India, Argentina, Bangladesh, Thailand and Taiwan are being reported to chronic arsenic exposure of as high as 2000 μg L^{-1} *via* drinking water.[8–11] In India, individuals in many districts within the states of Assam, West Bengal, Bihar, Uttar Pradesh, Chhattisgarh, Haryana, Jharkhand, Karnataka, and Punjab have been consuming groundwater with excess levels of arsenic.[12–14] Groundwater containing excess arsenic often exists alongside dissolved iron or Fe(II), but oxidation of Fe(II) to form insoluble Fe(III) hydroxide is a thermodynamically favourable reaction, particularly at near-neutral pH.[15] While arsenic-free surface water is an alternate solution, excess of such sources is not viable at all the time with challenges posed by water scarcity during dry spells and the issues of waterlogging and flooding during the monsoon season, especially in isolated habitations. In Assam, the adoption of family or community-based groundwater tube-wells has gained significant traction as a reliable source of drinking water, supplanting surface water for domestic use, while no depletion of water table is reported from any rural areas due to sufficient rainfall.

The Government of India has implemented various schemes over time to mitigate the issue of arsenic and support the development of drinking water infrastructure.[16] However, due to factors such as an increasing population, rapid development, and uneven resource distribution, the demand for water has surpassed the supply. Furthermore, inadequate institutional efficacy, resistance to reforms, and ineffective implementation of existing provisions have negatively impacted water supply in both rural and urban areas. Other factors that affect water supply in India include political will, environmental sustainability, social dynamics, technological economy, and appropriateness.[17,18] Despite the launch of the Jal Jeevan Mission Scheme in 2019, which aims to provide every household with functional household tap connections and adequate drinking water by 2024, challenges remain in achieving targets and providing quality water in regions affected by arsenic, fluoride, and other heavy metals.[19]

In such a scenario, it becomes imperative to adopt sustainable solution at the household level. Household point of use treatment is currently emerging as a viable alternative, especially in the emerging economies.[20–22] Researchers in recent times have focused on developing arsenic removal techniques that are of low cost as well as sustainable. Various physical, chemical, and biological techniques such as ion-exchange, reverse osmosis (RO), ultra-filtration, adsorption, coagulation, *etc.*, have been developed, tested, and employed for arsenic removal.[23–27] Ion-exchange, reverse osmosis (RO), ultrafiltration, *etc.*, are unsuitable for rural application in developing countries due to their drawbacks such as high costs, dependence on electricity, and generation of a large amount of sludge.[28] A popular method like RO, which is gaining popularity among the middle-class families, removes essential minerals from the water alongside concentrated contaminants as rejects in addition to its high cost of maintenance. Among alternative methods, adsorption and coagulation processes are popular and efficient.[29–32] However, many adsorption-based techniques are characterised by high material cost and require periodic replacement of the adsorbent. Coagulation–adsorption methods are popular, efficient and of low cost. Pre-oxidation is necessary to oxidise As(III) into easily removable As(V). Most of the arsenic removal methods based on oxidation–coagulation, currently used in Bangladesh, have low efficiency because of inadequate selection of chemicals, *viz.*, the pH regulator, the oxidant and the coagulant, and their doses.[26,33]

Oxidation–coagulation–adsorption at optimized pH (OCOP) using $NaHCO_3$, $KMnO_4$ and $FeCl_3$ as the pH regulator, oxidant, and coagulant, developed by our research group, has been gaining popularity in domestic and small as well as large scale community application as "Arsiron Nilogon" (arsenic + iron removal).[34,35] Studies have also confirmed its capability for efficient removal of heavy metals such as Cd, Co, Ni, Cu, Cr, Mn, and Pb along with arsenic and iron.[36,37] Although lab scale experiments and a small field trial of this method have been successfully conducted,[38] and the way the Arsiron Nilogon filter has been gaining popularity in several districts of Assam as well as in other states of India is noteworthy,[39,40] a validation of the rural technology with respect to its performance at large scale applications in villages and user acceptability is still due.

The goal of this systematic sustainability study was to determine the distribution of arsenic in the groundwater of Kuruabahi, one of the arsenic affected areas of Golaghat district in the state of Assam in India and validation of this rural technology as a large-scale community application for arsenic mitigation, where 320 such household units were installed.[41] Kuruabahi village is known to be a severely arsenic-affected village which has seen many cancer cases and other arsenicosis symptoms (Fig. 1), for which Numaligarh Refinery

Fig. 1 Digital photographs of suspected cases of arsenicosis from Kuruabahi village captured during field visits (PC authors).

Limited (NRL) offered funding under its corporate social responsibility for intervention of the problem with household filters using the do-it-yourself (D-I-Y) Arsiron Nilogon rural technology. It may be mentioned here that four of the families of Kuruabahi village had already been using self-made household Arsiron Nilogon filters. This study particularly aimed at assessing the technology by evaluation of its long-time performance, sustainability and user acceptance. A "triple bottom line" approach was used in the study to assess the overall sustainability of the filter, which was evaluated from the perspective of three elements, *viz.*, social, economic, and environmental sustainability, without delving in-depth into the sociological perspective.

2. Materials and methods

2.1 Study area

The present study area comprises four habitations, *viz.*, Chinakan, Adarsha Gaon, Rongagora, and Singadoria of Kuruabahi village (under Kuruabahi Gaon Panchayat) located in the Bokakhat circle of Golaghat district in Assam (Fig. 2). The details are provided in the ESI (SI-1).† Situated between the latitudes 26.68491° N to 26.65606° N and longitudes 93.69647° E to 93.72255° E, it is 3 km to the north of Numaligarh town and 43 km to the north of the district headquarter Golaghat. The Dhansiri river, a tributary of the river Brahmaputra, is a major river which meanders the four habitations from south, east, and

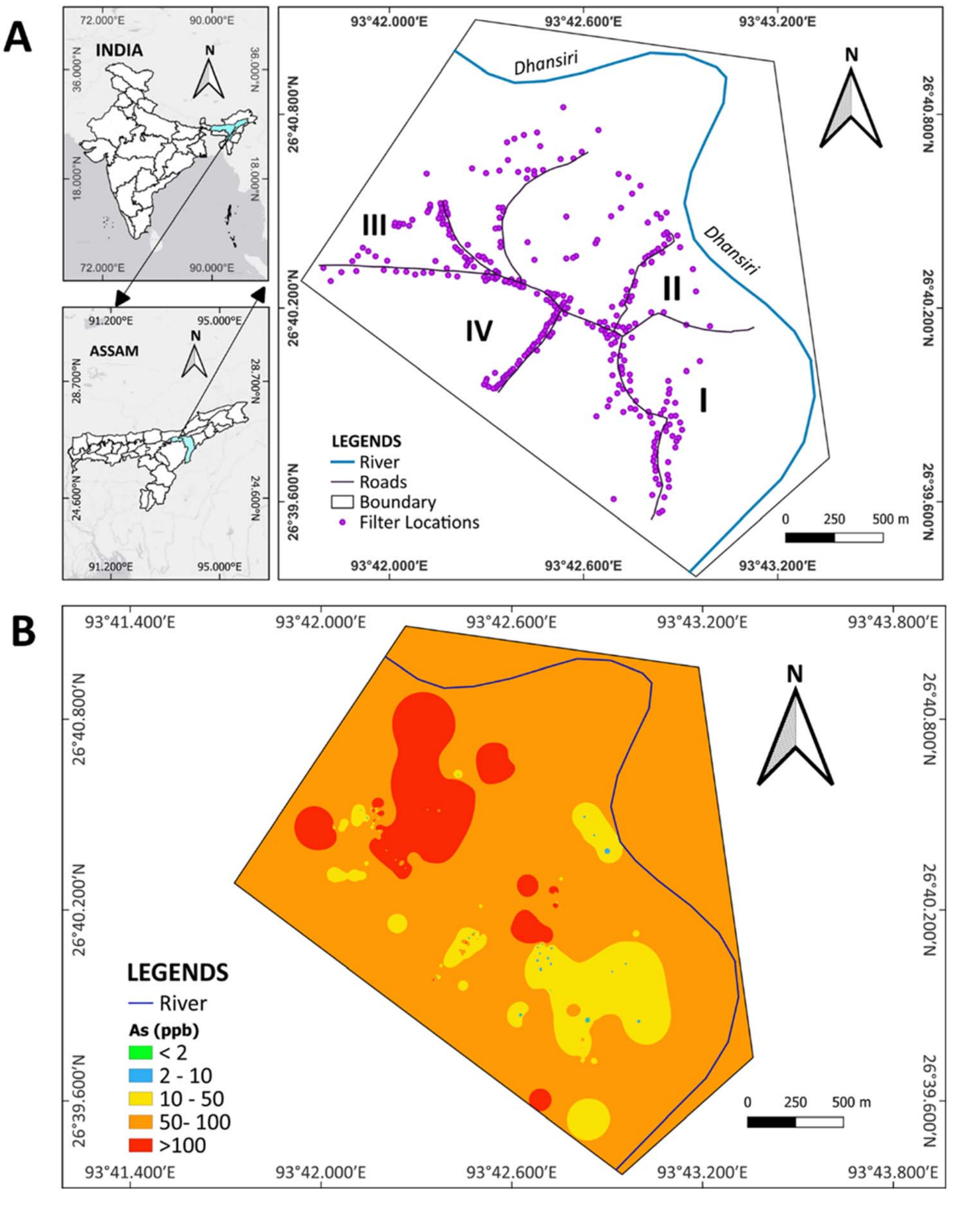

Fig. 2 (A) Sampling sites and filter locations at the four habitations of Kuruabahi, *viz.*, Chinakan (I), Adarsha Gaon (II), Rongagora (III), and Singadoria (IV). (B) Arsenic distribution in groundwater of Kuruabahi. These images were created using QGIS version 3.32-Lima (https://www.qgis.org/en/site/).

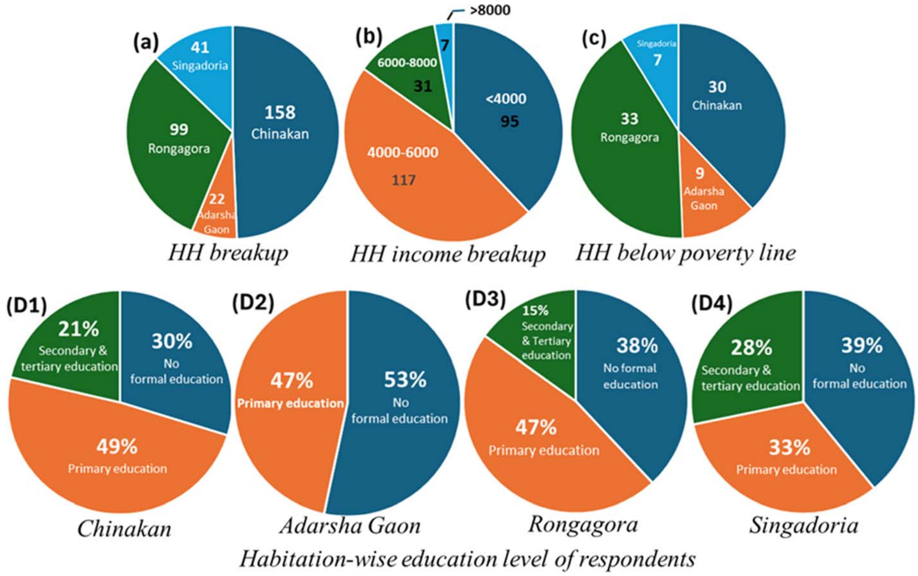

Fig. 3 Distribution of the (a) number of households (HH), (b) income distribution, (c) number of families below the poverty line and (D1–D4) proportion of respondents with respect to their educational qualification in the four chosen habitations of Chinakan, Adarsha Gaon, Rongagora, and Singadoria, respectively, with blue for no formal education, yellow for primary education, and green for secondary education.

north directions. The major source of water for drinking and other purposes of all the habitants is groundwater. The intervention was initially planned to cover 300 families to which twenty more families were added later. The distribution of the number of households is outlined in Fig. 3(a). The total population of these 320 families was 1355 as on 17th of December, 2021. There are four schools, including three primary and one secondary school, and three community cum prayer house, Namghars, in the village.

2.2 Filter materials and kits

The filter materials included a 40 L plastic drum fitted with a plastic tap for sedimentation of arsenic, a 16 L plastic bucket fitted with a plastic tap, about 20 kg sand, some gravel for making a sand gravel filter and an iron stand for placing the filter (Fig. 4). Technical grade $FeCl_3$ and $KMnO_4$ obtained from Lakshita Chemicals, Mumbai, and locally sourced $NaHCO_3$, a product of Tata Chemicals, Mumbai, were used as such for preparation of the kits for use in the village. Each kit included

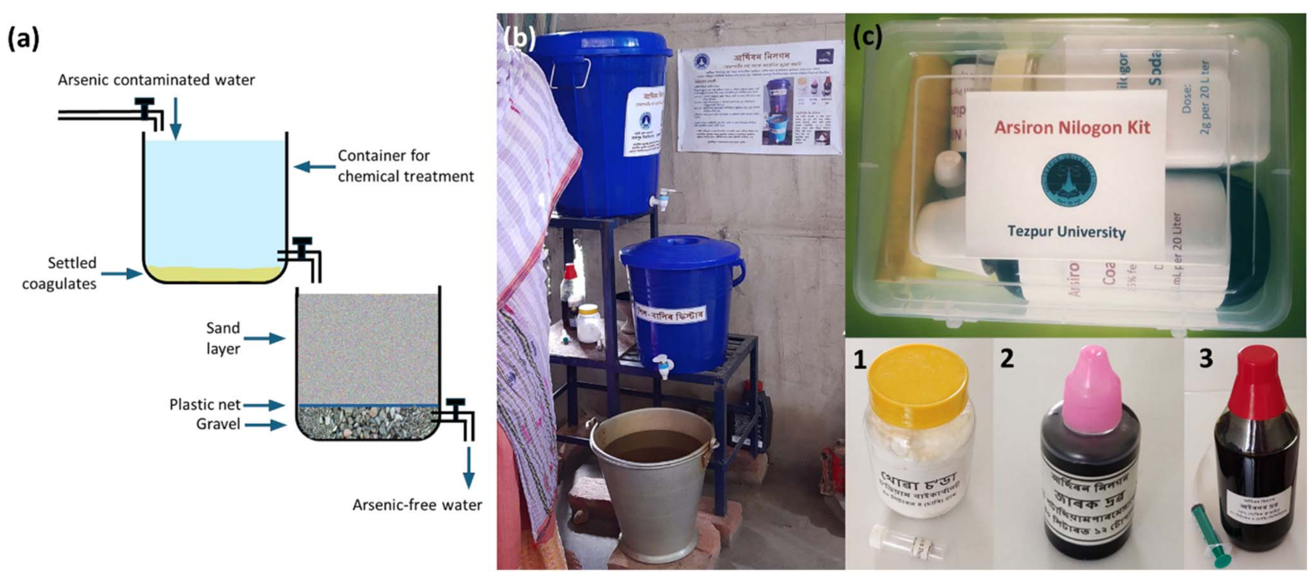

Fig. 4 (a) A schematic diagram of a Arsiron Nilogon unit; (b) a household Arsiron Nilogon filter installed at Kuruabahi with the upper container serving as a coagulation–sedimentation chamber, while the lower container is a sand-gravel filter; (c) a chemical kit which includes a bottle of 500 g $NaHCO_3$ (1) with a small measuring cup marked for 4 g for dispensing, a dropping bottle of 5% aq. $KMnO_4$ (2) and a 500 mL bottle of 25% aq. $FeCl_3$ (3).

(1) 500 g of baking soda (cooking soda, $NaHCO_3$) in a wide-mouth PET bottle with a 4 g measuring plastic cup, (2) 200 mL of 5% (w/v) aqueous potassium permanganate ($KMnO_4$) in a dropping bottle, (3) 500 mL of 25% (w/v) aqueous ferric chloride ($FeCl_3$) in a PET bottle, a marked 5 mL syringe for dispensing the solution, and a 30 × 45 cm^2 small poster describing the Arsiron Nilogon method and the operational procedure of the filter. Each chemical container was labelled with information about the chemical, its use, and precautionary measures.

2.3 Ethical statement

A verbal consent was obtained from an adult member from each family for participating in the study. All information was compiled in the form of a questionnaire during field visits after obtaining prior consent from the households. The questionnaire made for the purpose mainly focused on various aspects related to water such as the existing source of drinking water, current method of filtration, and awareness regarding arsenic contamination along with basic family details, income, and occupation.

2.4 The modality of implementation

2.4.1 The Arsiron Nilogon method. Arsiron Nilogon is used for treatment of water for removal of arsenic in the presence or absence of coexisting iron. The method involves sequential addition of small quantities of three common chemicals, which are commonly used in water purification, to the water to be treated at appropriate dose (Table 1), which takes about three minutes for a household filter. They are cooking soda powder, 5% potassium permanganate and 25% ferric chloride. The water is mildly stirred with a small bamboo or plastic stick for thorough mixing of chemicals while adding them. Coagulation, in the reddish-brown particles, is visible within minutes after addition of chemicals. The water is then filtered by a sand-gravel filter after one hour of residence time.

There are two options for Arsiron Nilogon for applications for water with dissolved iron. In option one, first, the dissolved iron is removed by simple sand-gravel filtration and then treated with Arsiron Nilogon as is done for water without dissolved iron. In fact, this is the way by which dissolved iron is usually removed from drinking water by villagers including the most at Kuruabahi. In option two, both arsenic and iron are removed together with a modified dose of chemicals. Given that most households utilised sand-gravel filters for the removal of iron prior to the implementation of the Arsiron Nilogon filters, it was recommended to first eliminate the existing iron from the water using those filters which also reduced the cost of the chemical ($KMnO_4$). Those who did not have such arrangements for removal of iron before Arsiron Nilogon treatment were provided with an additional 40 L plastic drum for the same.

2.4.2 Awareness, survey, and planning. In the first stage, a door-to-door visit was made, and a baseline household survey was conducted for proper assessment of the current water use pattern (ESI Fig. S1†) A household represents a family where all the members, including grandparents, parents and children, live together and share income, food, water, *etc.*[42] Creation of awareness among the people of the chosen habitations on arsenic contamination of drinking water, its adverse health effect, and importance of removal of arsenic from drinking water was imparted during the meetings with individual families during the door-to-door visits and through a series of four major workshops and awareness programs. One of such events was held at Tezpur University and the rest at Kuruabahi. A capacity building was done to prepare a group of six volunteers from each of the four habitations for helping in installation and training of the operation of the filters.

2.4.3 Sample collection. As all the villagers are using personal hand pump tubewells, they are the only source of water sample collection. A total of 292 groundwater samples were collected from hand pump tubewells covering all user families through door-to-door visits (ESI Fig. S1†). It may be noted here that 28 of the families did not have their own tubewells and used water from others' tubewells. The hand pump tubewells were pumped for 20 min before collection of samples. Separate water samples were collected for determination of As and other metal ions. Water samples were collected in acid prewashed 100 mL Tarson plastic bottles and were tightly closed. They were acidified to pH 0.015 or less using concentrated HCl and kept at least overnight for As determination. The samples were then pre-reduced with ascorbic acid so that arsenic in arsenate form does not escape detection. For detection of other metal ions, the samples were preserved in dilute HNO_3 (final concentration, 0.1%; pH < 2).[43]

2.4.4 Distribution and installation of filters. Field units of household level Arsiron Nilogon filters of 40 L capacity, each with accessories, chemical kits, and a mini poster on the Arsiron Nilogon method, were distributed, and the filters were installed in two phases due to COVID-19 travel restrictions. The filter and accessories included a 40 L plastic drum, for sedimentation of arsenic, fitted with a plastic tap and a sticker displaying the CSR sponsorship of NRL, a 16 L plastic bucket

Table 1 The doses of chemicals in Arsiron Nilogon in terms of weight per litre of water and their forms

Chemical	Dose	Form of the chemical
Cooking soda	0.1 gram per litre	White powder, or solution in water
Potassium permanganate	0.5 milligram per litre[a]	5% (w/v) aq. solution in water
Ferric chloride	25 milligram per litre	25% (w/v) aq. solution in water

[a] More potassium permanganate should be added, if the arsenic concentration is above 300 ppb or if iron is also present in the water, until the colour of potassium permanganate continues to disappear.

fitted with a plastic tap, about 20 kg sand, some gravel for making a sand gravel filter, an iron stand for placing the filter, and a mini poster briefing the Arsiron Nilogon method. In the 1st phase, 200 filters were installed in the month of April 2021, and this was followed by the 2nd phase of installing 120 filters in the month of August 2021. Majority of the installations were carried out by the users themselves as they had received extensive training. The installed filters and their use were supervised by the volunteers. Some of the users were aided by a group of six trained local volunteers. The group of six volunteers comprised individuals from the local community, and they assisted in the storage and distribution of filter materials and installation of filters. They underwent comprehensive training during a workshop conducted at Tezpur University (see ESI Fig. S2†). The group also included the local Councillor of Zila Parishad (ZPC), who played a pivotal role in overseeing various management tasks, including organisation of meetings, raising awareness, and facilitating storage and distribution of filter materials. Subsequently, every household and filter were revisited by the authors to evaluate the functionality of the filters, gather feedback, and collect samples of the treated water.

2.4.5 Follow-up. Systematic follow-up and monitoring were done after the distribution of the filter materials to check and ensure the proper functioning of the filters. The users were interacted with to know whether proper operating procedures were being followed for the filters. Treated samples were collected for testing of arsenic and other relevant water quality parameters. Telephonic and online monitoring were also made due to travel restriction imposed during COVID-19 lockdown periods.

2.5 Instrumental analysis

Arsenic and other metals ions were tested using a Thermo Fisher Atomic Absorption Spectrometer (AAS) (Thermo iCE 3000 series, USA) coupled with a Hydride Vapour Generator (HVG) and a Graphite Furnace (GF). The pH was determined using an Orion Multiparameter kit and a pH electrode (model: 5-Star pH/ISE/cond./DO Benchtop Meter, Orion, USA) with an error limit of ±0.01. In the field, a pocket-sized pH meter (model: HI96107, Hanna Instruments, USA) was used for determination of pH with an error limit of ±0.1.

2.6 GIS analysis and geospatial mapping

The spatial variability of the groundwater dataset was assessed through spatial interpolation using the Inverse Distance Weighting (IDW) approach in the QGIS 3.32-Lima desktop application. The resulting output was utilized to create geospatial distribution maps, illustrating the magnitude and distribution of arsenic across the four chosen habitations.

2.7 Sustainability study

The primary social indicators for evaluating sustainability included several aspects, including regular maintenance and use of the filter, collection of the chemicals, the influence of using the arsenic-free water on community health, *etc.* The enhancement in the taste and decrease in frequent acidity were commonly observed and examined in individuals who consumed filtered water on a regular basis. The economic sustainability for household Arsiron Nilogon was assessed based on the economic indicator of the so-called "Functional Unit" (FU), which is defined as the amount of water consumed for drinking by a typical household over a period of ten years, which is also the assumed lifespan for the filter. For example, in the case of Kuruabahi, the average household size was 4 persons. Assuming 2 L per day per person for drinking water,[21,44] the total amount of water consumed over ten years is estimated to be roughly 29 200 L per family.

3. Results and discussion

3.1 Socioeconomic profile of the users

Most of the inhabitants in Kuruabahi rely on agriculture as their primary source of livelihood. However, there is also a significant segment of population that depends on daily wages earned through labour. Only a very small portion of the population holds formal government jobs and occasionally venture into small trades. The financial status of most households is not very prosperous, with their average monthly income falling below INR 6000 per month per family, out of which seventy-nine respondents were found to be living below the poverty line in the survey (Fig. 3(b) and (c)).[45] A category wise breakup of their income is listed in Table 2. In terms of literacy, the residents of Adarsha Gaon had the lowest literacy rate, with 53% of respondents lacking formal education. Fig. 3(D1)–(D4) illustrates the distribution of respondents' educational qualifications across the four selected habitations.

3.2 Arsenic and pH in source water samples

Arsenic was tested in water samples collected from all the households. At all the households, tubewells form the prime source of water. The spatial variation of arsenic in groundwater obtained from testing the water samples before filtration is shown in Fig. 2. And the number of households with arsenic concentrations in drinking water in different concentration ranges are shown in Table 3. The highest arsenic concentrations were found as 344 ppb and 332 ppb at two tubewells of Rongagora and Chinakan, respectively. Among 320 households, 47 households were found to be consuming water contaminated with very high concentration of arsenic, *i.e.*, above 100 ppb,

Table 2 A breakdown of the income of the households of the study area

Monthly income (INR)	Number of HH	% w.r.t. total HH
<4000	95	29.69
4000–6000[a]	117	36.57
6000–8000	31	9.69
>8000	7	2.19

[a] The poverty line is considered.[39]

Table 3 Number of households with arsenic in drinking water in different concentration ranges

	Habitation-wise distribution of household in ppb				
Ranges (in ppb)	Chinakan	Adarsha Gaon	Singadoria	Rongagora	Total
<2	44	1	6	36	87
2 to <10[a]	18	2	2	4	26
10 to <50	40	1	8	24	73
50 to <100	37	15	22	13	87
>100	19	3	3	22	47
Total	158	22	41	99	320

[a] WHO provisional guideline value for arsenic in drinking water is 10 ppb.

Table 4 Arsenic contamination in some schools and Namghars (community places) at Kuruabahi village

Habitation	School/Namghar	Arsenic (ppb)
Singadoria	Pub Kuruabahi High School	266
Chinakan	Chinakan LP School	78
	Namghar, Chinakan 1	ND
	Namghar, Chinakan 2	80
Rongagora	Pub Kuruabahi M.E. School	16
	Kuruabahi Rongagora L.P. School	29
	Pujari Namghar	24

while a total of 207 households were found to be consuming water with arsenic above the WHO guideline of 10 ppb.[7] On the other hand, though the tubewell water of 113 households was found to be below 10 ppb, only 87 households of them had arsenic below 2 ppb or undetectable by AAS and the rest had arsenic concentration in the range of 2 to <9 ppb. It can be mentioned here that the guideline value of 10 ppb of WHO is only a provisional guideline value set due to proven toxicity of arsenic below 10 ppb and difficulty in detection and removal of arsenic below 10 ppb.[46] The pH of source tubewell water in Kuruabahi as measured on the spot was within the range of 6.32 to 7.13. Table S1 in the ESI† contains the detailed list of source pH values.

High arsenic contamination was found in drinking water of some schools and Namghars (community cum prayer halls) in the village as shown in Table 4. However, no community level Arsiron Nilogon filters could be installed at these community places as it was beyond the scope of the present CSR project.

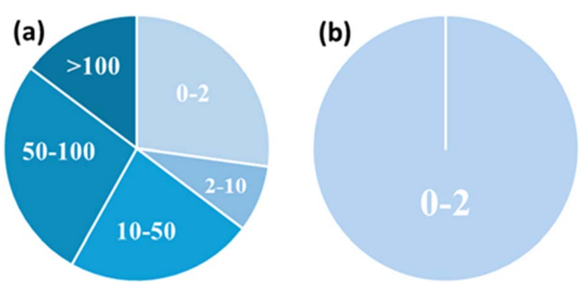

Fig. 5 Arsenic in different concentration ranges (ppb) before (a) and after (b) filtration.

3.3 Technical performance of the filters

The arsenic concentration in all 320 water samples treated by the household Arsiron Nilogon filters has been found to be undetectable or below 1 ppb (Fig. 5). The pH of all the treated samples was found to be 7.3 (±0.2), which is in the middle of the acceptable pH range of 6.5–8.5 for drinking water, as specified by the Bureau of Indian Standards (BIS).[47]

Four randomly selected treated samples, one each from the four habitations, were tested for some other relevant water quality parameters, and the results are presented in Table 5. Among the other heavy metals, only Fe was found to be present in the range of 1.69 ppm to 5.54 ppm in the water before treatment. Mn, Ni, Co, Cr and Al were below the detection limit and below the WHO guideline value. The water samples collected from same households after treatment of water from the same respective sources were also found to be free from Fe. All these treated samples show Fe below the detection limit of 0.01 ppm, which is below the WHO permissible limit of 0.3 ppm. Fluoride concentration was checked in the source water samples as it is a common groundwater contaminant in some parts of Assam. Fluoride concentrations in source waters were very low and were between 0.10 ppm and 0.22 ppm. Arsiron Nilogon does not affect the fluoride concentration of water, and as expected the fluoride concentrations after treatment were found to be exactly the same as before treatment. The TDS of the water samples before and after treatment was below 500 ppm.

We observed initial water clarity in the collected groundwater samples of Kuruabahi. However, upon exposure to atmospheric oxygen for around 15 minutes, the sample exhibited a noticeable increase in turbidity and a reddish-brown coloration, indicative of ferric hydroxide precipitation with a distinct metallic taste and odour. From the four randomly selected samples collected from four chosen habitations, the highest iron concentration of 5.54 ppm was observed in the untreated samples from Rongagora (Table 5). The treated water by our method generally does not impart any colour, taste, or odour. While improperly cleaned sand in the sand-gravel filter could potentially lead to initial odour issues, none of the villagers reported about it on subsequent visits. Furthermore, our collected samples exhibited no detectable odours or colour posttreatment (ESI Fig. S3†).

Table 5 Detailed analysis of arsenic and some relevant water quality parameters, including iron, some other heavy metals, fluoride, pH and TDS in one representative water sample from each habitation of Kuruabahi before and after filtration[a]

Habitation	Sample	[As] ppb	[Fe] ppm	[Mn] ppm	[F^-] ppm	pH	TDS ppm
Chinakan	Before	98	5.14	ND	0.14	6.49	138
	After	ND	ND	ND	0.14	7.3	169
Adarsha Gaon	Before	53	1.69	ND	0.10	6.66	175
	After	ND	ND	ND	0.10	7.3	265
Singadoria	Before	82	2.25	ND	0.19	6.58	221
	After	ND	ND	ND	0.19	7.3	266
Rongagora	Before	172	5.54	ND	0.22	6.50	110
	After	ND	ND	ND	0.22	7.3	149
WHO guideline value		10	0.3	0.4	1.5	—[b]	—[c]

[a] ND: not detectable using an AAS-HVG. [b] WHO does not have a guideline value for pH, but BIS considers 6.5–8.5 as the acceptable range of pH for drinking water in India. [c] No health-based guideline value is proposed by the WHO, but the BIS recommends the maximum desirable TDS as 500 mg L^{-1} and the maximum permissible level in the absence of a better source as 2000 mg L^{-1}.

We conducted a follow-up sampling during our subsequent visits to the field. Among the randomly collected samples from the treated water, eight samples were analysed for arsenic concentration, and the results are presented in Table S2 of the ESI;† all results were found to be below 2 ppb or below the detection level using the HVG-AAS.

3.4 Social sustainability

After successful installation, time-to-time visit has been made to assess and monitor the filter's performance and to check and ensure availability of the chemicals. Observations were also made to assess any potential impact on individuals' wellbeing or any difficulties faced by the users which are described below.

3.4.1 Relief from chronic acidity. Relief from chronic acidity is one of the major health benefits that has been observed in the people drinking filtered water regularly when enquired in the subsequent visits. The data presented in the form of a pie chart (Fig. 6) indicates that individuals from Chinakan, Adarsha Gaon, Rongagora and Singadoria have experienced relief from acidity at varying percentages, 16%, 13%, 29%, and 15%, respectively. It has been observed that those with average to severe problems of acidity are more benefited. This might be attributed to the fact that arsenic containing water have a positive correlation with dissolved iron and a negative correlation with pH.[48] The pH of untreated source water in Kuruabahi is within the range of 6.32 to 7.13. The water treated with Arsiron Nilogon filters brings the final pH to 7.3, which is very near to the neutral value of water in the pH scale. While poor diet and other factors like unhealthy lifestyle and timing of food and drinks may also contribute to the acidity, the findings indicate that water with low pH may also be a significant contributor to chronic acidity. Arsiron Nilogon has proven to be an additional benefit in addressing this issue.

3.4.2 Enhancement of taste. Many of the villagers reported that they found the taste of the treated water to be better than before. This is because of the slight increase in benign carbonate ions in water due to addition of cooking soda, sodium bicarbonate, to regulate the pH for facilitating arsenic removal.[49]

3.5 Availability of chemicals and user acceptability

Out of the four workshops and awareness programmes held for the purpose, the last one held at Kuruabahi specially emphasised on sustainability (see ESI Fig. S2†). A stock of chemicals, *viz.*, potassium permanganate powder and 40% aqueous ferric chloride solution, was maintained for at least one year post-implementation. The volunteers were trained for preparation and distribution of these chemicals such as 5% aqueous potassium permanganate and 25% aqueous ferric chloride solutions, by refilling the original bottles. The users were advised to purchase cooking soda from the local market. The time-to-time regular refilling of the 5% aqueous potassium permanganate and 25% aqueous ferric chloride solutions and buying the cooking soda by most of the villagers indicated the acceptability and sustainability of the Arsiron Nilogon filters in the village.

Several subsequent visits were made as a part of follow-up and study to assess the users' usability and acceptability of the filters two years postimplementation. These visits were also

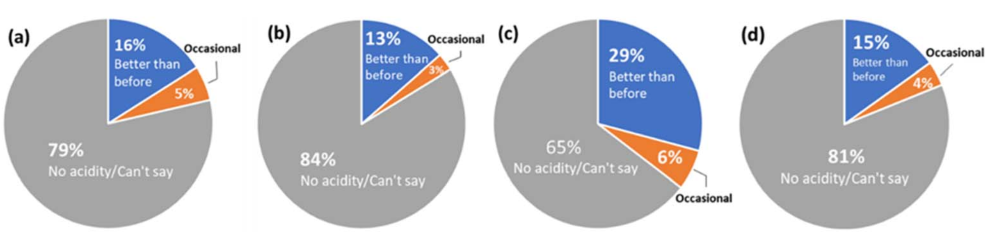

Fig. 6 The proportion of respondents (highlighted in blue) who have experienced relief from consistent acidity in Chinakan (a), Adarsha Gaon (b), Rongagora (c), and Singadoria (d).

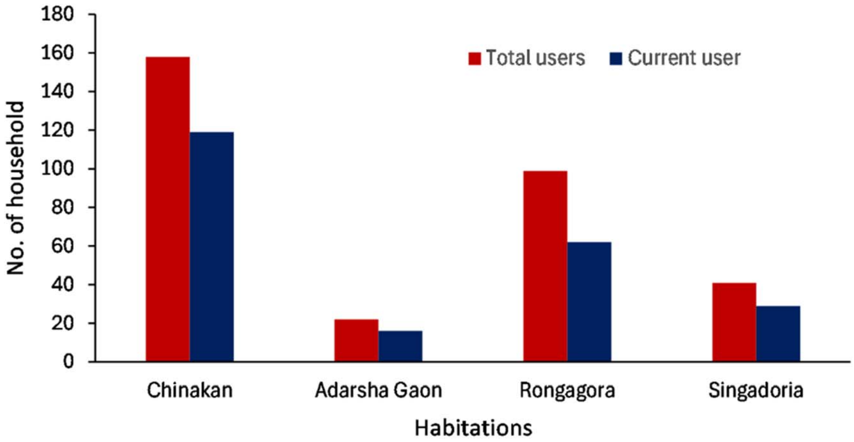

Fig. 7 No. of users by the end of two years postimplementation.

aimed to address any difficulty that could arise in use of the filters. While the percentage of user using the filer was 100% in the first year of implementation, it gradually declined in the subsequent year. The users' percentage by the end of second year was found to be 75.31%, 72.72%, 62.62% and 70.73%, respectively, for Chinakan, Adarsha Gaon, Rongagora and Singadoria, which make an overall percentage of 70.63% (Fig. 7). The decrease in the proportion of users over the following years were found to be linked to a range of factors, including the breakdown of plastic drums during relocation and displacement due to floods, lack of awareness, particularly amongst the illiterate population, and others.

Use of chemicals is sometimes said as a drawback of Arsiron Nilogon, but the chemicals used here are safe and common chemicals. Sodium bicarbonate is used in cooking, and potassium permanganate was earlier used as a mouth wash. Ferric chloride consists of iron and chloride ions which are common in groundwater, a source of drinking water. Moreover, all three chemicals are used in water purification worldwide. The most important advantages of Arsiron Nilogon are its high efficiency, low cost, D-I-Y nature, no requirement of power, no loss of water, tiny and safe solid sludge, *etc.*, far exceeding any disadvantages of using chemicals.

3.6 Economic sustainability

The primary measure of economic viability for any water treatment technology is the cost of one Functional Unit (FU). For Arsiron Nilogon, it was first necessary to compute the recurring as well as the capital cost. Considering the retail prices of sodium bicarbonate, potassium permanganate, and ferric chloride at US $0.36, US $4.11, and US $0.55 per kilogram, respectively, the current method's recurring treatment cost was calculated to be US $0.055 per m^3 of treated water. A household Arsiron Nilogon filter distributed at Kuruabahi consisted of two plastic buckets of food grade quality, one each of 40 L capacity which is priced at US $3.58. Additionally, the filter came with two plastic taps priced at US $1 each. The sand and gravel per filter together cost US $0.36, which was sourced from the nearby river and local market, respectively. Consequently, the capital cost of a 40 L household Arsiron Nilogon at Kuruabahi amounted to US $9.52. Considering an estimated filter lifetime of ten years and considering the recurring as well as the capital cost, the direct cost to the consumer for delivery of one FU was approximately US $10.865.

3.7 Environmental sustainability

A very small quantity of sludge that was produced was collected in an earthen pot containing sand and a small hole at the bottom by the villagers themselves as advised. The sludge passed the toxicity characteristic leaching procedure (TCLP) test of the United States-Environmental Protection Agency (US-EPA) for dumping it even in a landfill. The TCLP test showed the arsenic concentration in the TCLP leachate of the sludge sample to be less than 10 ppb, much lower than the TCLP limit of US-EPA.[50] The sludge was usually buried at a safe place so that the arsenic cannot easily be leached into water. During the follow-up, all the households were found to have followed an appropriate sludge disposal method as advised.

4. Conclusions

The present study shows severe contamination of arsenic in the groundwater of Kuruabahi village of Golaghat district of Assam. To mitigate it, household Arsiron Nilogon filters were successfully installed in all the 320 households, even in an unfavourable situation prevailing during COVID-19. All filters have been found to be effective in bringing down arsenic concentrations from as high as 344 $\mu g\ L^{-1}$ to being undetectable by the AAS-HVG method of detection or below 2 $\mu g\ L^{-1}$. The substantial rate of approval by the users and the proportion of regular users indicate that the recipients are satisfied with the clean arsenic-free water from the filters. The pH of the mostly slightly acidic water was found to be 7.3 after treatment, which gives an added health benefit of the Arsiron Nilogon filters by enhancement of the taste of water and alleviating chronic acidity in some people within the community. The assessment of social, economic, and environmental factors convincingly suggest that the low-cost Arsiron Nilogon filter represents a sustainable choice for rural point of use household application. This study also demonstrates the scope for scalability of the Arsiron Nilogon filter. The successful implementation of household units in this village highlights its broader application across diverse settings such as community schemes owing to its customisable nature. Arsiron Nilogon, being a do-it-yourself method, relies on user awareness and knowledge of proper operation of the method. If properly trained and timely monitored, it can serve as a stop gap arrangement until arsenic-free surface water is made available and as a standby system for use during interruptions in surface water supply in the long run with minimum intervention requirement.

Data availability

The data supporting the findings of this study are available within the article and its ESI file.† The open-source software tool used for part of the GIS analysis and geospatial mapping is available at [https://www.qgis.org/en/site/]. Additional data related to this research can be accessed upon reasonable request from the corresponding author.

Conflicts of interest

There are no conflicts to declare.

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