Water Security 20 (2023) 100150

Contents lists available at ScienceDirect

Water Security

journal homepage: www.sciencedirect.com/journal/water-security

Adaptable community participatory design to provide water that is *Estético, Seguro, y Saludable* (pleasant, safe, and healthy) in the Ecuadorian Amazon

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ARTICLE INFO

Keywords:
Water treatment
Participatory research
Biochar adsorption
Retrofit infrastructure
Chemical toxicants

ABSTRACT

A pedagogical framework was developed for water that is aesthetically pleasant, microbiologically safe, and healthy from a chemical perspective for consumption by vulnerable individuals and over lifetimes. This “pleasant, safe, and healthy” framework was used to facilitate discussion of drinking water source selection and design of treatment approaches with Ecuadorian Amazonian communities affected by petrochemical and agrichemical pollution and partially or totally lacking in centralized water infrastructure. Iterative participatory discussion identified biological slow sand filtration and biochar adsorption as unit processes for addressing microbiological and chemical water contaminants with which communities had some prior familiarity. However, significant shortcomings and knowledge gaps were discovered in extant approaches that led to poor treatment performance and disuse of previous water interventions. A workshop was conducted to bring communities’ and local implementers’ understanding and abilities in line with current best-practices for sustainable provision of pleasant, safe, and healthy drinking water using local materials.

1. Introduction

A partnership between Aqueous Solutions international WASH consultants (aqsolutions.org), based in North Carolina, USA, and two Ecuadorian grassroots sustainable development organizations, *Amisacho Restauración* (amisacho.com) and *La Clínica Ambiental* (clinicambiental.org), is developing decentralized water treatment solutions for rural and *peri*-urban communities in the Ecuadorian Amazon. This region has suffered decades of heavy petrochemical pollution (Fig. 1) along with lack of water infrastructure and poorly maintained infrastructure, leading to biological and chemical pollution of surface water bodies, shallow aquifers, and tube wells [1,2]. Lack of water infrastructure can indicate inadequate supply, lack of treatment or inadequate treatment of drinking water and/or wastewater to address all necessary dimensions of water quality. Poorly maintained water infrastructure can signify, for example, leaking distribution systems that permit ingress of pollutants and malfunctioning wastewater collection and disposal systems. This has caused massive pollution of the Amazonia ecosystem, killed wildlife, and contaminated water sources with a wide range of toxic compounds. Additional chemical water pollution in the region originates from agrichemical-intensive cropping of export commodities [3,4]. Local indigenous populations have suffered a variety of diseases, including cancer and birth defects, from exposure to petrochemicals and agrichemicals through drinking water, wild foods such as fish, and bathing in contaminated streams [5–7].

Aqueous Solutions is working with *Amisacho Restauración* and *La Clínica Ambiental* to develop local capacities for using biochar water treatment to provide safe drinking water to communities affected by petrochemical pollution. This practitioner commentary describes our approach to ongoing and evolving work in WASH provision. First, we describe the “*Estético, Seguro, y Saludable*” (“Pleasant, Safe, and Healthy” or PSH) water quality framework as a pedagogical (i.e., teaching and learning) tool for communicating key water quality concerns, and for understanding, assessing, and selecting appropriate treatment methods for the local context. We describe a workshop that took place in September 2022 in *Lago Agrio*, northeastern Ecuador, that used the PSH framework to inform water source selection and treatment system design for the hands-on portion of the workshop constructing the system. Our activities dovetail with other pedagogical approaches that have been developed across the global engineering, development, and water sectors [8–10].

We then describe two case studies developed from iterative

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https://doi.org/10.1016/j.wasec.2023.100150
Received 25 November 2022; Received in revised form 17 October 2023; Accepted 26 October 2023

Fig. 1. Waste oil pit and gas flare. Over 1,100 surface waste pits and around 447 gas flares exist within the provinces of Sucumbíos and Orellana in the Ecuadorian Amazon to contain waste oil and production fluids and burn off excess methane [17]. They are significant sources of air, water, and soil pollution.

discussions with locals that embody a "Modular, Adaptive, and Decentralized" (MAD) approach to WASH. MAD is an emergent theme in WASH provision that promotes the deployment of sustainable WASH infrastructure that is scalable and adaptable to local needs [11]. Our case study first involved leveraging existing but poorly functioning infrastructure in combination with workshop participants' gained capacities to support retrofitting existing infrastructure to improve treatment performance. Our case study then supported locals' self-reliance in provision of water treatment to remove harmful petro-/agri-chemicals using a homemade biochar filter-adsorber. Our approach is consonant with of a variety of participatory and human-centered design approaches that have improved the success and sustainability of WASH projects and anti-poverty projects more generally [8,10,12].

2. *The* Estético, Seguro, y Saludable *(Pleasant, Safe, and Healthy) water quality framework*

This project provides a case study that advances multiple key dimensions of transformational WASH [13]. One, water sources are contaminated by and must be treated for modern chemical pollutants (petrochemicals, agrichemicals) in addition to traditional microbiological pathogens of fecal origin [14–16]. Two, the project does not start from a "blank slate," but builds upon existing capacities, knowledge, experience, infrastructure, and history of WASH interventions in the region through iterative participatory discussion with community implementers. Three, it embodies a MAD approach to WASH [11] by (a) enabling retrofits of existing WASH infrastructure along with implementation of new infrastructure where appropriate, and (b) adaptively incorporating multiple water sources including decentralized as well as centralized (i.e., municipal piped water) systems for redundancy and resilience in water supply.

The "Pleasant, Safe, and Healthy" framework as pedagogical tool

To support sustainability and self-reliance in WASH provision, we take a pedagogical approach with the objective to develop community members' and local implementers' conceptual understanding and technical appreciation of multiple dimensions of water quality (e.g., the distinction between biological and chemical water contaminants), how different water sources can be vulnerable to different types and amounts of water contaminants and thus can be assigned relative ranking of highest to lowest putative quality as source waters for drinking, and how different dimensions of water quality often require individuated treatment approaches (e.g., separate unit processes). Accordingly, our partnership has developed the *Estético, Seguro, y Saludable* (Pleasant, Safe, and Healthy, PSH) pedagogical framework for communicating different water quality concerns and treatment options.

In this lexicon, "Pleasant" refers to water free from aesthetic problems – undesirable tastes, odors, and/or appearance. "Safe" refers to water free from acute illness causing microbial pathogens. "Healthy" signifies water free from cumulative health threats that accrue over long periods of consumption and affect the most vulnerable individuals such as fetuses and newborn infants, pregnant women and lactating mothers, the ill, infirm, and elderly [13–16]. Such health threats can arise from exposure to chemical toxicants such as herbicides and pesticides, industrial and petrochemical waste substance, endocrine disrupting compounds, and geogenic contaminants such as fluoride and arsenic [13–16].

One example of drinking water provision in low-resource circumstances that is gaining widespread acceptance and that can be explained using the PSH pedagogical framework is a treatment train consisting of three unit processes in series: a gravel roughing filter followed by a biological slow sand filter followed by a biochar adsorber, as depicted in Fig. 2.

Discussion of the individual unit processes shown in Fig. 2 and how each addresses one or more components of the PSH water framework is a useful pedagogical exercise for developing understanding of different water quality challenges and how modular and adaptive treatment techniques can be combined in context- and site-specific approaches to decentralized water provision. For example, the gravel roughing filter primarily addresses the *pleasant* component through the removal of turbidity that gives water an undesirable appearance and possible poor taste. However, it also addresses the *safe* and *healthy* components by providing some removal of pathogen cells and chemical pollutants sorbed to sediment particles through settling. The biological slow sand filter primarily addresses the *safe* component by removal of pathogens, but also improves water aesthetics by removal of fine sediments (*pleasant* component) and biodegradable chemical pollutants (*healthy* component). The biochar adsorber primarily addresses the *healthy* component by removal of dissolved chemical pollutants, but also supports better water aesthetics e.g., through the removal of color and/or odors (*pleasant* component) and provides an additional barrier to pathogen exposure (*safe* component).

Community participatory discussion of PSH water source selection and provision

Common water sources in the region include rooftop harvested rainwater, tube wells, surface water bodies, and municipal piped water for some *peri*-urban communities. The PSH framework was used to facilitate a discussion of different water sources and routes for potential microbiological and chemical contamination. Surface waters were recognized as the most vulnerable to contamination from erosion, agrichemical runoff, petrochemical spills, wastewater/sewage discharge, and dump/landfill leachates. Tube well water was assessed to likely range in quality depending upon depth, integrity of the well and casing, and potential for exposure to subsurface plumes of septage and/

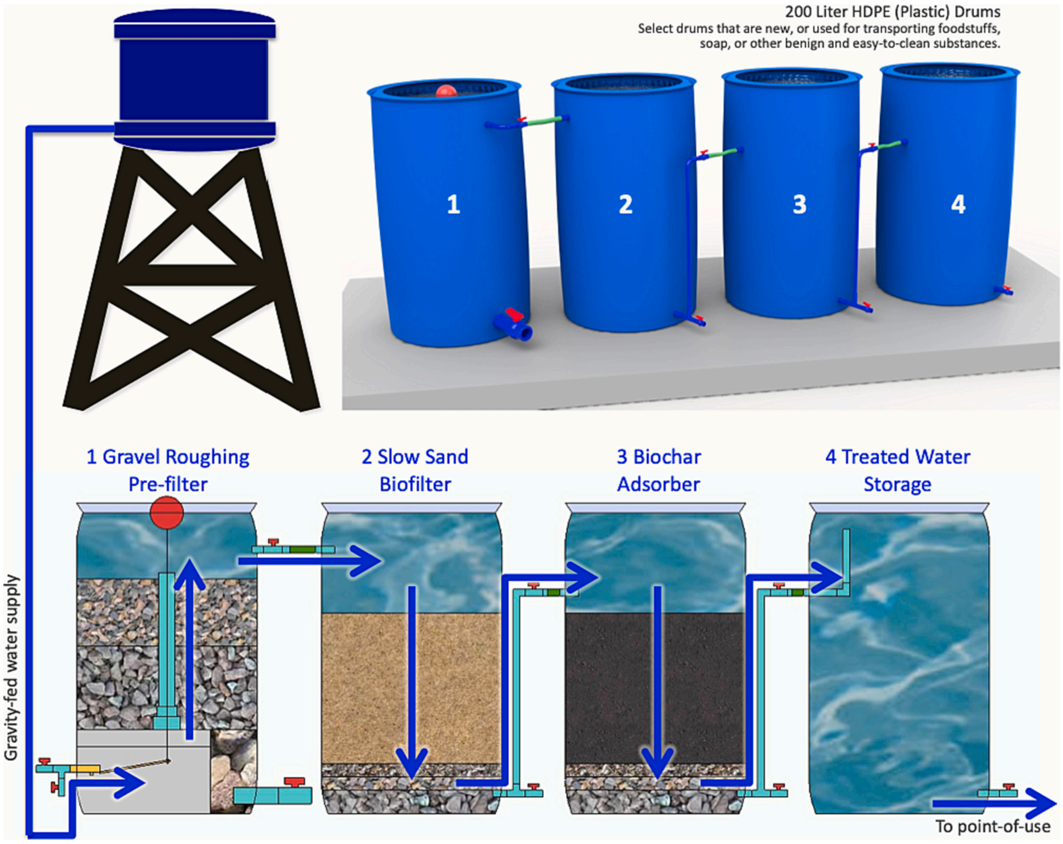

Fig. 2. Treatment flow diagram for 300 L/day water system incorporating gravel roughing filtration, biological slow sand filtration, and biochar adsorption. Source: aqsolutions.org.

or agrichemical/petrochemical infiltration. Rainwater was regarded as a high-quality source with potential for contamination by bird and animal droppings, air pollution and deposited soot from gas flares, and contaminated storage tanks. Discussion with local municipal authorities revealed that municipal piped water – typically sourced from major surface water bodies such as the *Rio Aguarico* – receives partial treatment for sediment removal and chlorine disinfection, but is vulnerable to recontamination through leaks and clandestine connections in the aging distribution network. During the workshop, discussion of water sources using the PSH framework facilitated communities' identification of rooftop harvested rainwater and municipal piped water as likely highest quality source waters available in many cases.

Building on community experiences and retrofitting extant infrastructure

Communities and local implementation non-governmental organizations (NGOs) have basic familiarity with using biological slow sand filtration for controlling pathogens in rooftop harvested rainwater, and with using activated carbon or charcoal for removal of dissolved organic chemical contaminants. However, existing treatment approaches that have been implemented throughout the region do not follow best practices and therefore function poorly. A core workshop objective was to increase community members' and implementers' understanding of the relevant science and engineering principles behind biological slow sand filtration and biochar adsorption to enable retrofitting of poorly functioning treatment systems and support future implementation of new treatment systems in accordance with best practices.

Previous work by an NGO in the region (Amazon Frontlines, amazonfrontlines.org, [18,19]) installed 1164 systems that integrated rainwater harvesting with biological slow sand filtration. Other local NGOs active in the region such as the *Unión de Afectados por Texaco* (UDAPT, texacotoxico.net), and *Frente de Defense de la* Amazonia (makechevroncleanup.com) use the same design promoted by Amazon Frontlines.

Conversations with community members and leaders suggested that many of these systems are underutilized or have fallen into disuse. Community members reported that water storage tanks failed to fill, and that sand filters may have clogged with sediment and debris. An objective of the workshop was to convey sufficient conceptual background and key design parameters to support best practices in implementing biological slow sand filtration. This knowledge could be used to retrofit existing, poorly functioning, systems to raise them to acceptable performance standards, or design new treatment systems adapted to different contexts.

An internal evaluation conducted by Amazon Frontlines [19] revealed that "83 % of pre-filter samples and 85 % of post-filter samples had no fecal coliforms," noting that the difference between these values was not statistically significant. Fecal coliforms were only measured in eight samples of influent waters. The study is thus severely lacking in statistical power. Of the eight influent waters with mean fecal coliform concentration of 27.5 colony forming units (cfu) per 100 mL, a statistically non-significant reduction of 68 % was observed in slow sand filter effluent (mean fecal coliform concentration of 8.7 cfu/100 mL) [19]. Were this result statistically robust, it would indicate unacceptably poor function of sand filter units. Properly designed and operated biological slow sand filter units are capable of 4–5 log (99.99 % to 99.999 %) removal of pathogenic cysts and oocysts (e.g., giardia, cryptosporidium), and a minimum of 1–3 log (90 %-99.9 %) removal of bacteria and viruses [20,21].

Inspection of the diagram and photo shown in Fig. 3 reveals several shortcomings of this system design that could explain poor performance in water collection as well as inadequate treatment. These include: lack of a first-flush system, excessive loading rate of the sand filter, and inadequate depth of the sand filter bed and/or improper outlet pipe height. Existing systems do not incorporate a first-flush system to prevent sediment and debris accumulated on the roof structure from

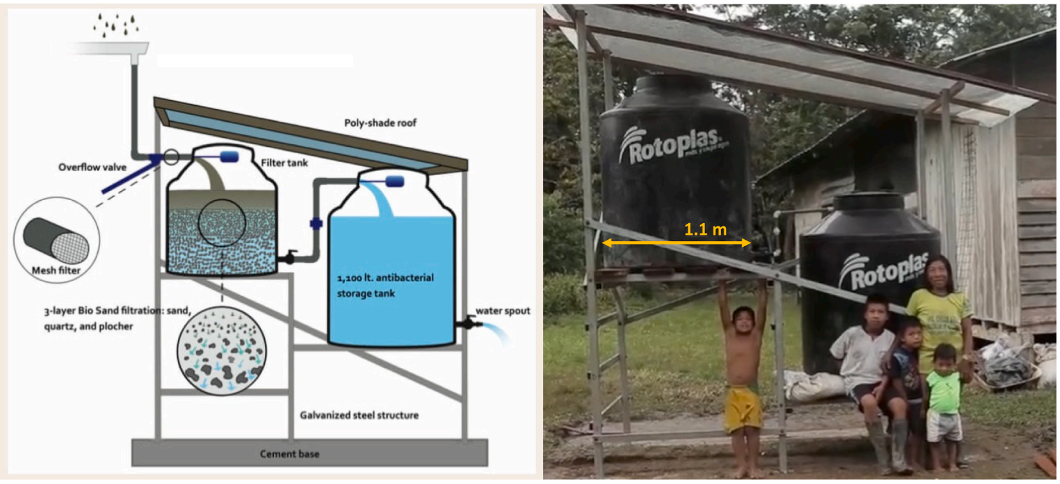

Fig. 3. Systems for collecting and treating rainwater implemented by Amazon Frontlines. Diagram and photo accessed from the website of Amazon Frontlines [18,19].

entering the sand filter. Over time this could lead to clogging of the sand filter causing it to overflow and limiting collection of treated rainwater. This could be an explanation for why some communities discontinued use of systems due to lack of water capture.

Existing systems transfer rainwater directly from collection roofs to the sand filter rather than to a retention tank prior to filtration. In this configuration, the ratio of sand filter area to roof collection area is insufficient for maintaining filter hydraulic loading rates within

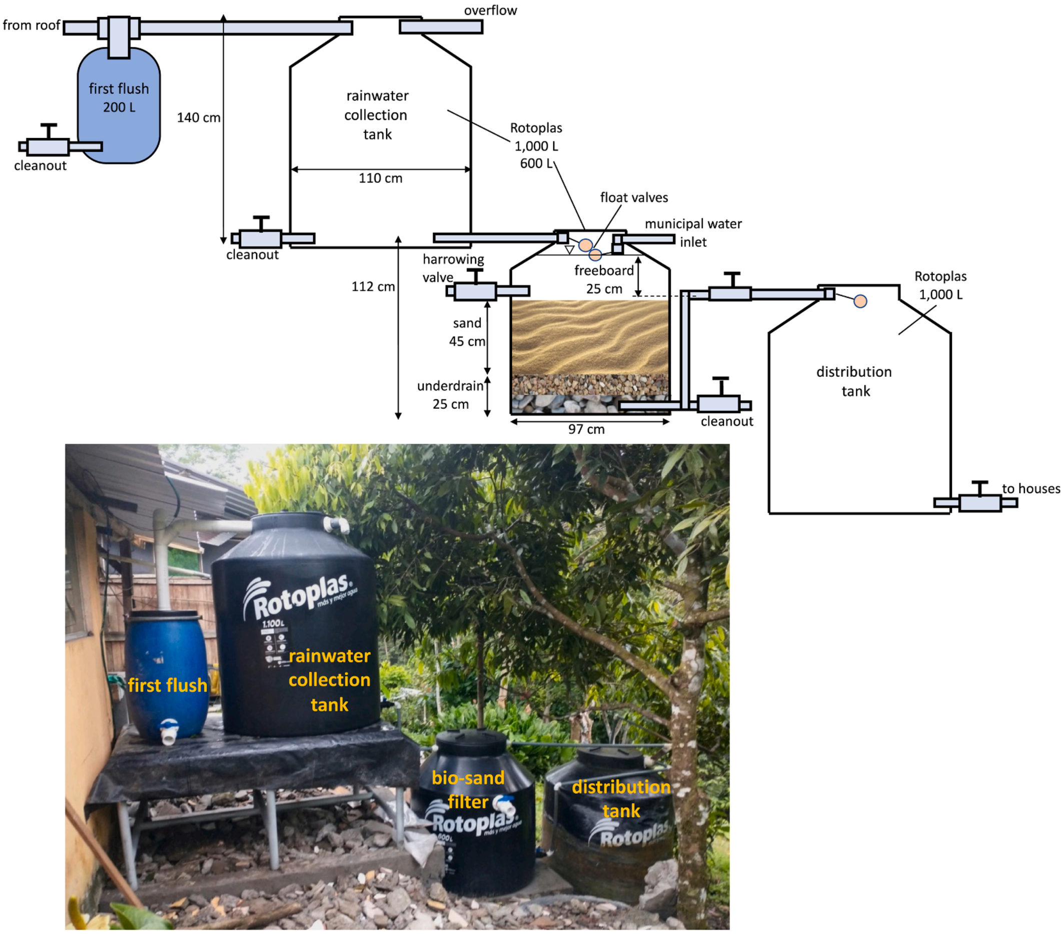

Fig. 4. System for collection and treatment of rooftop harvested rainwater with municipal piped water supply as a secondary source. A "first-flush" tank captures sediment and contamination washed off of the roof during the first few minutes of a rainstorm. Locating the municipal piped water inlet float valve slightly below the inlet rainwater float valve ensures treatment of rainwater when available and activates treatment of municipal water once the rainwater collection tank is depleted. The freeboard (vertical distance between water level and filter outlet pipe) of ~ 25 cm means that for a hydraulic conductivity of 10 m/d (typical for slow sand filters) the maximum loading rate of the filter would be 0.23 m/hr according to Darcy's law (i.e., near the design loading rate of 0.2 m/hr). Water is distributed by gravity to a cluster of homes located lower in elevation than the treatment system pictured.

acceptable ranges during medium to heavy rain storms. As described in the workshop, best-practice maximum loading rates for slow sand filters are 0.1–0.3 m/hr [20,22,23]. For 10 m^2 of roof collection area (the approximate area of the roof structure shown in the photo in Fig. 3 and much smaller than a typical home roof area), a slow sand filter constructed from a *Rotoplas* 1,100 L tank as shown (1.1 m diameter) rainstorms of strength to 1.0–2.8 cm/hr (0.39–1.1 in/hr) would produce filter loading rates within maximum acceptable levels (0.1–0.3 m/hr). Heavier rainstorms typical of the Amazonian tropical climate would exceed maximum recommended slow sand filter loading rates, impairing treatment.

Existing systems appear to have either too shallow sand bed depths, or have outlet pipe heights set too low, or both. Biological slow sand filter outlet pipe height should be set at least a few cm above the level of the sand such that the biofilm always remains submerged and therefore does not dry out and thereby impair treatment function. Minimum recommended bed depth for slow sand filters is 45 cm [20–23]. Materials available from Amazon Frontlines' website [18,19] do not specify sand bed depths. Estimating from the photo shown in Fig. 2 and other treatment system photos on Amazon Frontlines' website, either sand filters suffer from biofilm drying out due to improper outlet pipe height and/or insufficient sand bed depth.

An iterative, participatory process was used to develop an adaptable biological slow sand filter design following best practices (e.g., minimum bed depth, maximum loading rate) that could serve as a retrofit of existing nonoptimal infrastructure or deployed as new infrastructure. Improvements over existing systems include: incorporation of a first-flush system to divert accumulated sediment and contaminants washed off of the roof during the first minutes of a rainstorm, placement of a rainwater retention tank before the biological slow sand filter unit, installation of a harrowing valve for facilitation of filter cleaning, loading rate control through outlet pipe height, and accommodation of multiple water sources.

The system installed as a hands-on learning activity during the workshop allowed for capture and treatment of rainwater as a primary source with municipal piped water, where available, as a backup during periods of little rain (Fig. 4). Rainwater was given preference over municipal piped water as it was seen to be less vulnerable to chemical contamination compared with municipal water sourced from surface water bodies. Moreover, municipal authorities stated that water treatment facilities are not equipped to remove dissolved chemical contaminants such as petroleum hydrocarbons and herbicides. The workshop installation exercise illustrates an approach to MAD-water (modular-adaptive-decentralized) [11], and furthermore one way that a decentralized water supply and treatment module – rooftop harvested rainwater with biological slow sand filtration – can be adapted to also utilize centralized (piped) water distribution as redundant supply to bolster resilience in water access. Further modularity is discussed in the next section on tiered treatment approaches to optimize labor and materials costs while providing fit-for-purpose water quality to different household uses.

A biological slow sand filter of the size shown in Fig. 4 (*Rotoplas* 600 L, 0.97 m diameter) can provide up to 3,550 L/day of treated water at a hydraulic loading rate of 0.2 m/hr, which falls within recommended operational guidelines for slow sand filters [20,22,23].

Regarding chemical water contaminants, Amazon Frontlines' website and Webb (2018) [18,19] state the following: "[the layers of sand and crushed quartz] trap contaminants such as toxic metals and petroleum pollution, which stick to the sand as they flow by in a process called adsorption." However, this is not the case; sand and "crushed quartz" are not effective adsorbents for removing dissolved organic chemical pollutants such as petrochemicals, or heavy metals. Removal of organic petrochemical contaminants (and some metals) can be accomplished by an additional treatment step using activated carbon or biochar adsorbent, as discussed in the next section

Supply chain sustainability considerations: locally generated biochar adsorbent for water treatment.

La Clínica Ambiental has incorporated an approach to biochar adsorption for removal of petrochemical and agrichemical toxicants into its educational curriculum on household and community water treatment. To save time and labor, *La Clínica* recommended using cooking charcoal sold in local markets in water treatment units. However, research has demonstrated that cooking charcoal at best achieves modest adsorption performance compared with a commercial activated carbon benchmark [24–27]. At worst, cooking charcoal made at low temperature (350–550C) is not completely carbonized and contains tarry and oily residues that can leach into water causing taste, odor, and color problems and also posing potential health risk.

Traditional charcoal manufacture processes are not optimized for producing biochar adsorbent for water treatment [26]. Other research has shown biochar produced at high temperature (≥850C) in semi-aerobic gasifier units to exhibit adsorption performance comparable to commercial activated carbon, and 10–100 times better than cooking charcoal [24–27]. An objective of the workshop was to instruct community members and local implementers including *La Clínica* in the process of making low-cost water treatment biochar from local surplus and "waste" biomass using a gasifier drum oven (Fig. 5a).

During the workshop, participatory discussion revealed a preference for a two-tiered treated water quality design. Treatment by biological slow sand filtration alone for pathogen control was deemed adequate for many household uses such as washing clothes, handwashing, bathing, and washing dishes. Treatment by biological slow sand filtration followed by biochar adsorption to additionally remove dissolved chemical toxicants was desired for drinking water and for use in food preparation. This two-tiered design, which treats only a small fraction (~15 %) of total household water use to levels appropriate for consumption was preferred due to the savings of time, labor, money, and resources used to construct small household biochar adsorption units in place of large biochar contactor(s).

A collaborative process was used to arrive at a simple and inexpensive design for a point-of-use biochar adsorber constructed from a commonly available 20 L plastic water dispenser (Fig. 5b). The unit contains 10 L of biochar adsorbent and can produce 30 L/day of treated water when used as recommended. After one year of use the biochar is replaced with fresh adsorbent.

3. Conclusion

The PSH framework is a useful pedagogical tool for engendering critical and creative thought about different dimensions of water quality, water source selection, and the design and integration of different treatment modules (unit processes) for provision of treated-to-purpose water for a range of household uses in in adaptive ways that are often context- and site- specific for resource constrained settings. This initiative highlights how participatory discussion and design using the PSH framework can elevate unique contextualized approaches to water self-provision, for example through combining centralized (e.g., piped water) and decentralized (e.g., household harvested rainwater) sources to bolster water security through redundancy and accommodation of one or more backup sources.

The workshop built on existing local infrastructure, experience, and capacities to retrofit and refine approaches to biological slow sand filtration and biochar adsorbent generation that follow best practices. The collaboration also demonstrated the advantages of a tiered approach to highest-quality-first water sourcing as well as value engineering treatment systems according to water use (e.g., appropriately sizing flows for domestic uses versus consumption).

This case study integrated pedagogical and technological approaches to WASH provision using MAD water principles and implemented a participatory design. We hope that our approach to informing community members and local implementers in the requisite science and engineering concepts for achieving adequate water treatment affordably

Fig. 5a. Left: co-author Muñoz describing biochar gasifier drum oven operation for workshop participants. Upper right: Muñoz preparing a demonstration of making water filter biochar from chopped reject broomstick wood. Lower right: reject broomsticks burned for disposal behind carpentry shop.

Fig. 5b. Co-author Yepéz demonstrating point-of-use household biochar adsorber developed through participatory design workshop.

using local locally available resources can be replicated around the world.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Acknowledgments

The authors thank *La Clínica Ambiental* for providing funding support for this project, and the residents and staff of *Amisacho Restauración* for hosting the workshop.

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