UNIVERSITY OF OXFORD

Rural Water Treatment Barriers and Opportunities: An Implementation Science Analysis of Chlorine and UV-C LED Disinfection in Small Water Supplies

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List of abbreviations

CAS	Complex adaptive systems
CDB	Chlorine-dosing bucket
CUREC	Central University Research Ethics Committee
DBPs	Disinfection by-products
FCR	Free chlorine residual
HIC	High-income country
IS	Implementation Science
IUVA	International Ultraviolet Association
JMP	Joint Monitoring Programme
LMIC	Lower - middle-income country
NTU	Nephelometric Turbidity Units
O&M	Operations and maintenance
PC	Passive chlorination
PoC	Point-of-consumption
PoU	Point-of-use
RCT	Randomized Controlled Trial
SDG	Sustainable Development Goal
TCCA	Trichloroisocyanuric acid
UV-C LED	Ultraviolet – C Light Emitting Diode
WASH	Water, Sanitation and Hygiene
WHO	World Health Organization

Abstract

Critical developments are needed within rural water service delivery models to align with Sustainable Development Goal 6.1. This study focuses on the implementation of passive chlorination and ultraviolet (UV) disinfection for water treatment. Both technologies reduce health risk from microbiological contaminants in drinking water; a key difference is the effectiveness of UV against pathogens like cryptosporidium versus the ability for chlorine residuals to provide continued protection. Based on a synthesis of existing research, an implementation science framework (RE-AIM) was employed to uncover the necessary improvements needed for sustainable long-term implementation. A qualitative content analysis of 26 stakeholders involved in passive chlorinator and UV projects in rural areas in South America, Africa and Asia, revealed key implementation trade-offs. The results identify challenges in securing local supply chains, ensuring financial sustainability, and establishing service delivery models. Recommendations focus on local collaboration, creative financing strategies, and contextualization of technologies.

1 | Introduction

In order to align with Sustainable Development Goal (SDG) 6.1: universal and equitable access to safe, affordable drinking water, critical developments must be made within rural water service delivery models. Access to safe drinking-water is not only essential to human health, but is also a basic human right and a key component of broader health-related policies (UN 2010; WHO 2022). However, in 2020, one in four people lacked access to safely managed drinking water, amounting to 2 billion people worldwide (UNICEF/WHO 2021). Moreover, eight out of ten people lacking even basic drinking water services were living in rural areas, and urban coverage of safely managed services is higher than rural coverage in all SDG regions (UNICEF/WHO 2021). Not only can the lack of access to clean drinking water result in a number of serious health implications, but it may also lead to furthered social and economic inequalities (Hoque et al. 2019; Crider 2021).

To increase access to safely managed drinking water in rural areas, decentralized water treatment approaches focus at the household-level (point-of-use, PoU) or community-level (point-of-collection, PoC). A high level of adherence is required to realize positive health outcomes from water treatment, but household-level practices have low uptake and sustainability in many contexts (Boisson et al. 2013; Enger et al. 2013). Household-level water treatment places an additional burden on individuals, which is often gendered (Crider 2021). This study focuses, therefore, on the implementation environment of community-level water treatment, looking specifically at passive chlorination (PC) and ultraviolet-C light emitting diode (UV-C LED) disinfection. Both technologies reduce health risk from microbiological contaminants in drinking water; a key difference is the effectiveness of UV against robust pathogens like cryptosporidium versus the ability for chlorine residuals to provide continued protection between treatment and end use (Malayeri et al. 2006; Adeyemo et al. 2019; Deem et al. 2022). There are also important differences in the maintenance and financing regimes required to sustain these technologies, including components of end-user perception and communication.

An implementation science approach, namely RE-AIM, is employed to uncover the facilitators and barriers to successfully and sustainably implementing decentralized water treatment in order to realize positive health outcomes and enhance climate resilience (Shelton et al. 2020). This approach was selected because implementation science has been shown to be advantageous in filling the gap between efficacy studies (i.e. technological research) and real-world application (Theobald et al. 2018; Rosenthal et al. 2020).

1.1 Research gap

Systems thinking cannot be categorized as a single method, tool, or discipline; instead, there are many different approaches from a range of different fields (Neely 2019: 17). Complex adaptive systems (CAS) can be defined as "systems that co-evolve with their environment, show self-organization and emergent properties, are non-linear in their dynamics, are sensitive to initial conditions, and show a certain level of 'stability' due to feedback processes that create homeostasis" (Neely 2019: 22). Considering this definition, this study will refer to the term "systems" as CAS, which include the local context, management, supply chains, sustainability factors, and other themes described in more detail from Chapter 3 onwards. Physical water supply and treatment "systems", however, will be referred to purely as "technologies" or "infrastructure".

Few studies are available summarizing and mapping the systems surrounding these low-cost water treatment interventions, thus the impacts of key components of implementation such as maintenance, user perception, and financing are poorly understood (Lindmark et al. 2022). This research addresses this knowledge gap through an implementation science assessment of past and current PC and UV-C LED water disinfection projects in rural, resource-constrained settings. Particularly, the primary research gap this study focuses on is uncovering the necessary improvements needed for sustainable long-term implementation and the steps required to shift in this direction. The secondary gap is the lack of studies comparing chlorination and UV implementation factors, which this research aims to fill. The literature review chapter will further explore the current gaps and uncertainties of this research space.

1.2 Research objective and questions

The core objective of this research is to uncover the facilitators and barriers to successfully and sustainably implementing decentralized water treatment in order to realize positive health outcomes and enhance climate resilience in rural, resource-constrained settings, primarily in lower- and middle-income countries (LMICs). Based on the research gap previewed in section 1.1, the following three research questions (RQs) were established:

RQ1: What are the main factors that determine the sustainability of implementing treatment in rural water supplies?

RQ2: How do these factors collectively constitute an enabling environment for safe rural water supply?

RQ3: How consistent or variable is the enabling environment with respect to different technological approaches?

1.3 Dissertation structure

Following this introduction, Chapter 2 of this dissertation provides a background of the research and literature on the health impacts of WASH, drinking water quality and decentralized water treatment, and describes PC and UV-C LED technologies in further detail. Chapter 3 explores implementation science and the RE-AIM conceptual framework as the basis of this research. Chapter 4 describes the methods and research design, including key informant interviews, thematic analyses and systems mapping analyses. Chapter 5 offers the key findings of the research. Chapter 6 discusses these findings within the context of policy recommendations, areas for future research, and broader implications of development projects. Finally, Chapter 7 summarizes the final conclusions of the study.

2 | Literature review

2.1 Profiling the current state of WASH

Globally, we are not on track to meet the Sustainable Development Goal 6 "Ensure availability and sustainable management of water and sanitation for all", specifically target 6.1 of "universal and equitable access to drinking water for all" (UN 2015). Many parts of the world currently face extreme challenges to provide a consistent supply of safe drinking water to their populations (WHO and UNICEF 2019). In 2017, the Joint Monitoring Programme (JMP) estimated that 435 million people used unimproved water sources, and 144 million people still used surface water (WHO and UNICEF 2019). Geographically, 80% of those lacking even basic services lived in rural areas, and almost half lived in LDCs (WHO and UNICEF 2019). The JMP shows that 29% of the global population relies on a water source that is fecally or chemically contaminated (WHO and UNICEF 2019). Furthermore, the issues are particularly prominent in Sub-Saharan Africa and South Asia, with less than 75% of the population having access to safe water facilities (Oskam et al. 2021).

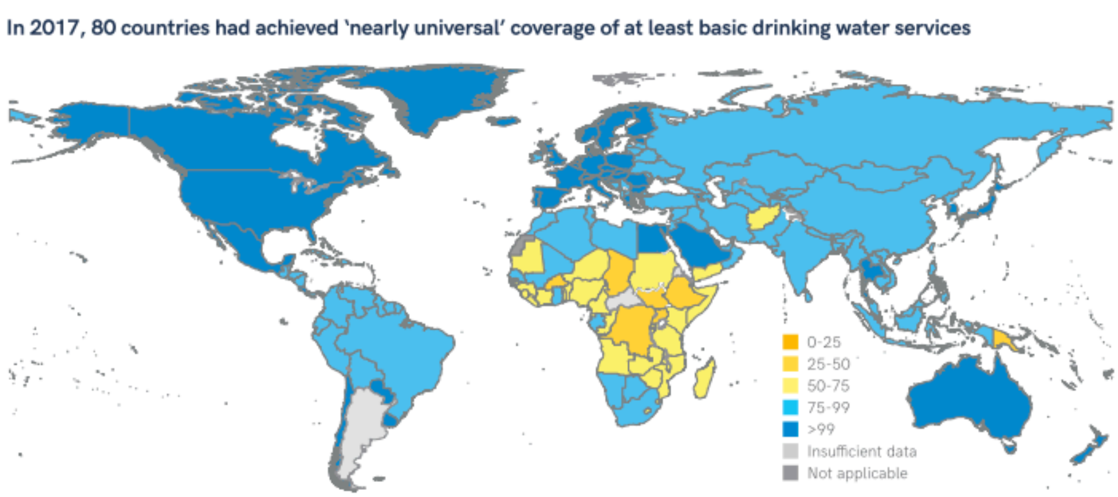


Figure 1: *Proportion of population using at least basic drinking water services, 2017 (%) (WHO and UNICEF 2019)*

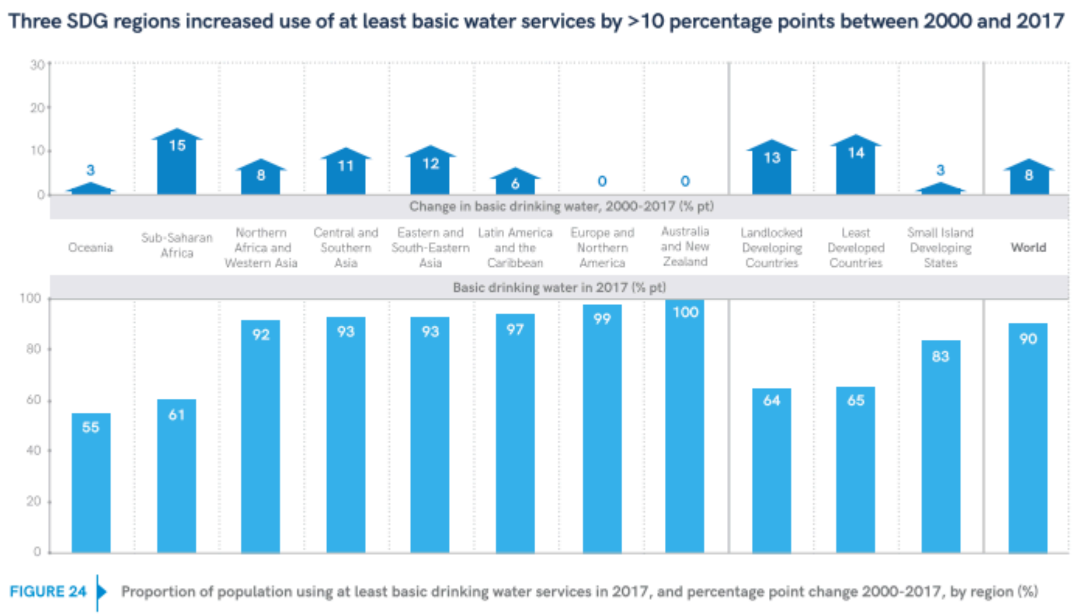


Figure 2: *Proportion of population using at least basic drinking water services in 2017, and percentage point change 2000-2017, by region (%) (WHO and UNICEF 2019)*

As LMICs are often restricted by water scarcity, limited electricity for pumping, and financial constraints, amongst others, it remains an obstacle to provide clean water at all hours of the day (Kumpel and Nelson 2013). Additionally, water could be safe at the source, but the high risk of (re)contamination during distribution may lead to unsafe water at the PoC (Kumpel and Nelson 2013). Global population growth in combination with an unsustainable demand for groundwater indicate that intermittent water supply and subsequent risks are becoming more frequent (A. J. Pickering et al. 2019).

Poor Water, Sanitation and Hygiene (WASH) practices are associated with dangerous health impacts, including enteric infections, diarrheal disease, schistosomiasis, soil-transmitted infections, and nutritional deficiencies (e.g. stunting) (Clasen et al. 2007; Freeman et al. 2017; Gakidou et al. 2017). The use of public health interventions in the early 20th century has been shown to reduce mortality and disease rates (Cutler and Miller 2005). For example, between 1900 and 1940, the United States mortality rates declined by 40%, primarily due to reductions in infectious disease which were associated with clean water technologies (Cutler and Miller 2005). The consequences of unsafe drinking span beyond negative health impacts: they may also affect and worsen gender, social, and economic inequalities (Sorenson et al. 2011; Oskam et al. 2021). The burden of household water treatment is most often placed on women and girls, further worsening existing gender inequalities (Fisher 2008).

There is a strong foundation of biological evidence that improvements in WASH services result in a decline in negative health impacts; however, there is a growing body of high-profile randomized control trials (RCTs) of low-cost interventions that indicate minimal to no reductions in childhood diarrheal disease or undernutrition from these interventions (Kirchhoff et al. 1985; Boisson et al. 2010; Jain et al. 2010; Boisson et al. 2013; Clasen et al. 2014; Patil et al. 2014; Clasen et al. 2015; A J Pickering et al. 2015; Luby et al. 2018; Null et al. 2018; Humphrey ScD et al. 2019). Research also shows that technological solutions may offer promising solutions to water quality issues, but expected results are rarely realized in practice (Sesan et al. 2018; Clasen and Smith 2019). Thus, there is a need for further research into holistic solutions and systems-based approaches to the implementation of health interventions in the WASH sector (Neely 2019).

2.2 Water quality and decentralized water treatment

When considering drinking water treatment, many different aspects must be taken into account. The main types of contaminants may be microbial, chemical, or radiological (WHO 2022). In order to ensure the safety of drinking water, a host of different barriers should be implemented, ranging from source protection, carefully selected water treatment technologies, and properly managed distribution (WHO 2022). The primary source of microbial contaminants is from human or animal feces, which may result in the spread of pathogenic bacteria, viruses, protozoa or helminths (WHO 2022). Disinfection is used as an effective barrier against pathogens in drinking water treatment, and can be done with the use of chemicals (e.g. chlorine), through boiling, or UV irradiation, amongst others (WHO 2022). Each form of treatment has its limitations and specific requirements, thus making it essential that treatment approaches are matched to the local context.

While decentralized water treatment is not new, a recent shift to focus on passive forms of water treatment prior to the PoC is taking place, alongside centralized options in some contexts. Household-level water treatment, including filters, solar disinfection, boiling or chlorination, has been very common for years (Brown and Clasen 2012). While effective on a technological basis, studies indicate that high adherence of PoU water treatment is required for positive health impacts to be realized (Luoto et al. 2011; Enger et al. 2013). From an economics standpoint, one study found that less than 30% of households in poor communities in Dhaka used chlorinators even when provided free of charge (Luoto et al. 2011). Wolf et al.'s meta-analysis found that adjusting estimates for the absence of blinding may reduce the effect of PoU interventions, looking specifically at decreasing the prevalence of waterborne illnesses through interventions (Wolf et al. 2018). Overall, the responsibility, and consequent burden, of treatment falls on the household, and often to women and girls, creating a bigger barrier to acquiring safe drinking water sources (Brown and Clasen 2012). Indeed, transformative investments are needed in the safe water sector to move towards utility-scale service models, so as to shift this burden away from households (Ray and Smith 2021).

Specifically, this study focuses on two forms of PoC water treatment, namely PC and UV-C LED disinfection. These two types of technological approaches were selected based on their high level of uptake and research interest to-date, as well as their increased technological advancements in recent years (Lui et al. 2014; Lui et al. 2016; A. J. Pickering et al. 2019; Oguma and Watanabe 2020; Lindmark et al. 2022).

2.3 Disinfection through passive chlorination

Passive, in-line chlorination is a form of water treatment that is low-cost and does not require power or electricity; this lowers the labor burden and removes behavioral barriers associated with PoU products (Mintz 1995; Mintz et al. 2001; Amin et al. 2016; A. J. Pickering et al. 2019; Dössegger et al. 2021). In comparison to manual chlorination, in-line chlorination automatically doses tablet or liquid chlorine into water flowing from a pipe, tap, or pump, either at the point of collection or upstream (Amin et al. 2016; Dössegger et al. 2021; Smith et al. 2021). Although the technologies still require some level of maintenance, the primary responsibility for operation is shifted from individual households to either elected community members, engineers, or a service delivery organization (Crider et al. 2019).

2.3.1 Types of passive chlorinators

Currently, there exists a range of different types of commercially accessible passive chlorinators or manuals to build them based on locally accessible materials, each with specific benefits or suitability to specific infrastructure. PC technologies may vary widely and are not all appropriate for all settings (Figure 3; Figure 4); however, evidence and support for appropriate technology selection remains limited (Crider et al. 2019). Factors that differentiate chlorine technologies include "(i.e., solid versus liquid), cost, maintenance frequency, and compatibility with flowrates and pipe size" (Crider et al. 2019).

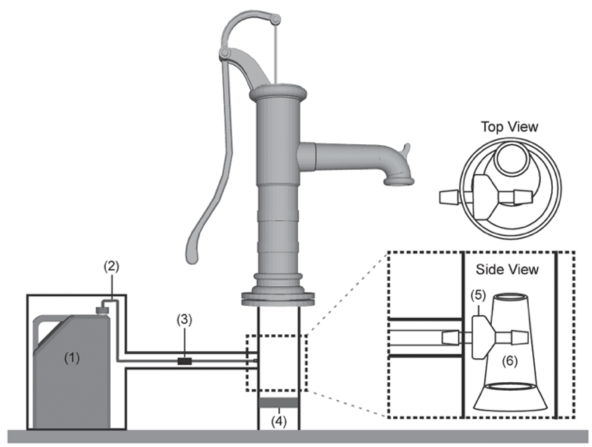


Figure 3: *Schematic of passive chlorinator used at a handpump (Amy J. Pickering et al. 2015)*

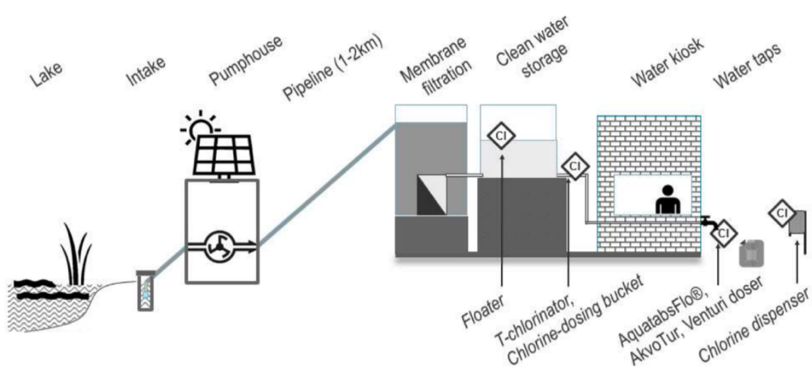
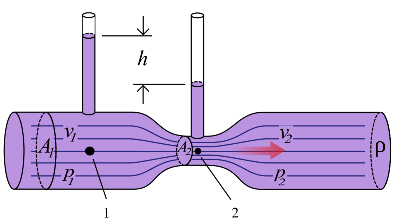


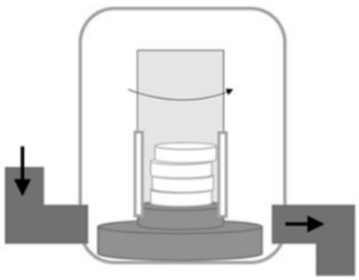
Figure 4: *"Scheme of GDM kiosk showing the different installation locations of assessed chlorinators" (Dössegger et al. 2021)*

The following table provides a brief overview of a selection of different types of chlorinators (Table 1).

Table 1: *Overview of selected chlorinators*

Image	Type and Description
 (Dössegger et al. 2021)	**Floaters (chlorine tablets)** Floaters are commonly applied when chlorinating swimming pools; however, the technical manual also identifies the possibility for using it for drinking water treatment (Oxfam 2001).
 (Dössegger et al. 2021)	**T-chlorinators (chlorine tablets)** T-chlorinators are shaped as an upside-down T, and can be built using PVC piping, which are most often locally available materials. They can be used in a gravity-fed piped distribution network, and are user-friendly and robust technologies. They use slow-dissolving trichloroisocyanuric acid (TCCA) chlorine tablets (Orner et al. 2017; Dössegger et al. 2021).
 (Venturi effect, Wikipedia)	**Venturi doser (liquid chlorine)** Venturi-style dosers employ the Venturi effect for dosing chlorine into the water, namely by having water pass through a compression in the pipe, leading to an increased water flow velocity and an increased pressure difference at the constriction. This, in turn, causes the liquid chlorine to be pulled into the water. The device needs to be installed before the tap. It consists of fragile parts and is currently not yet commercially available, and is thus still relatively expensive (Dössegger et al. 2021; Powers et al. 2021).

AquatabsFlo (chlorine tablets)
AquatabsFlo are produced by Medentech (based in Ireland) and function using cartridges filled with sodium dichloroisocyanurate (NaDCC) tablets that are dissolved when water flows through them. The device must be installed after the tap. The cartridges must be fully replaced when the chlorine tablets are used up, creating quite an increase in overall costs (A. J. Pickering et al. 2019; Dössegger et al. 2021).



AkvoTur
Based on the AquatabsFlo design, these devices must also be installed after the tap. However, they have a better mechanism for chlorine tablet refills. Materials are generally available locally, but they generally work best with 1'' TCCA tablets, which can be difficult to procure in some countries (Dössegger et al. 2021).

Chlorine (manual) dispenser
Manual chlorinators (chlorine dispensers) require users to chlorinate their water themselves, and have been widely installed in Kenya, Uganda and Malawi by organizations like Evidence Action (Hodges 2017).

2.3.2 Advantages of passive chlorination

One of the primary benefits of chlorination is the continual disinfection of water provided by chlorine residuals, namely during distribution and storage processes (A. J. Pickering et al. 2015; Crider et al. 2019; Dössegger et al. 2021). PC, as opposed to manual chlorination, is not dependent upon user compliance, thus removing this labor burden from individual households. Furthermore, PC is a relatively low-technology intervention, which does not require any electricity, that can be implemented in rural, resource-constrained settings. The use of chlorine for disinfecting drinking water has been widely employed and thus there is a wide body of evidence supporting its use (Lantagne et al. 2008; A. J. Pickering et al. 2015; Rayner et al. 2016; Crider et al. 2019).

2.3.3 Limitations of passive chlorination

On the other hand, PC has some limitations and risks. Chlorine has varying levels of effectiveness against different microorganisms (Cervero-Aragó et al. 2015), as they may have different resistance to it based on surface properties and how they may react to chlorine as an oxidant. For example, it is not very effective against cryptosporidium (Chalmers et al. 2019), as well as some viruses, which indicates the need for some additional form of treatment, like filters or UV (Adeyemo et al. 2019). Additionally, chlorination does not work well in turbid waters as the turbidity protects microorganisms from disinfection (Mitro et al. 2019). From a social perspective, chlorinated water may cause issues related to taste and odor, as well as cultural or religious issues in some contexts (Crider et al. 2018). An unintended consequence and potential risk of drinking water chlorination is the generation of disinfection by-products (DBPs), specifically trihalomethanes, which are formed when chlorine reacts with natural organic matter (Li and Mitch 2018). Some studies suggest that there is an association between the consumption of water containing DBPs and adverse health impacts, such as bladder cancer and miscarriages (Waller et al. 1998; Costet et al. 2011). Limits on trihalomethanes in drinking water are important to strike a balance between disinfection from microbial contaminants and the risks of DBPs, such as 1979 Total Trihalomethane Rule put in place in the US, limiting THM4 to < 100 µg/L (Federal Register 1998). However, the WHO indicates that the "risks to health from these by-products are extremely small in comparison with the risks associated with inadequate disinfection, and it is important that disinfection efficacy not be compromised in attempting to control such by-products", while a recent population-based cohort study found no association with an increased risk of bladder cancer (Helte et al. 2022; WHO 2022).

2.4 Disinfection through UV-C LED technologies

Ultraviolet (UV) irradiation is an effective form of drinking water treatment that is capable of inactivating a broad spectrum of microorganisms without the use of chemical consumables or residual taste/odor, and has previously been applied in the form of mercury-based UV devices (Bolton and Cotton 2008; Lui et al. 2016). At high UV doses, or fluences, microorganisms are inactivated through the absorption of UV photons by proteins in the outer cell membranes, leading to disruption and consequent death of the cell (Bolton and Cotton 2008). At lower fluences, the ability of the microorganism to replicate is disrupted, meaning it can no longer cause infection (Bolton and Cotton 2008).

2.4.1 Advancements in UV-C LEDs and current operationalization

UV-C light-emitting diodes (LEDs) have recently advanced technologically resulting in reduced cost, increased output power, and improved lifetime. Lui et al. found that, at the time of the study in 2016, commercially available UV-C LEDs were already technically effective in inactivating *E. coli* and *E. faecalis*, and offered advantages in terms of speed and energy demand (Lui et al. 2016). Furthermore, Simons et al. calculated a 39% compound annual growth rate (CAGR) in commercial single-chip LED output power over the period of 2005 to 2022, which exceeds Haitz's Law, where Haitz's Law is the forecast that every decade, the cost per lumen falls by a factor of 10 and the light generation per LED increases by a factor of 20 (Simons et al. 2022). In line with this speedy development, published data and information about the development of UV-C LEDs very quickly become outdated (Simons et al. 2022). Compared to conventional mercury-based bulbs that require a warm-up time and thus must be in continual operation, LEDs may remain in low-power standby mode and only need to be engaged on-demand (Simons et al. 2022).

2.4.2 Advantages of UV-C LEDs

There are a range of advantages to UV-C LED water treatment. Firstly, there are no issues related to taste and odor as there is no use of chemical consumables (Hull et al. 2019). Further, due to its mechanism of action, it causes damage to all nucleic acids and proteins upon which microbial pathogens rely and is agnostic to the taxa of the microorganism; thus, UV is highly effective in inactivating a broad spectrum of microorganisms (Oguma and Watanabe 2020). However, microorganisms do have varying susceptibilities to UV irradiation, where for example, cryptosporidium is easily inactivated and viruses are much more difficult to inactivate (Malayeri et al. 2006; Water Research Foundation 2015). New research is showing that low UV wavelengths can, in fact, be very effective at inactivating microorganisms that were previously found to be very difficult, like viruses, but these technologies are not yet commercially available (Beck et al. 2018;

Hull and Linden 2018). As mentioned earlier, the rapid advancement of LED efficiencies serve for UV-C LED disinfection to become a more affordable, and thus widespread form of water treatment (Simons et al. 2022).

2.4.3 Limitations of UV-C LEDs

On the other hand, several disadvantages of UV-C LED based water treatment exist. There remains a reliance on some form of energy access, which is often not available in more rural, resource-constrained settings. However, with the advancement of technologies coupled with solar power, this may become a less critical issue in the future (Lui et al. 2014; Lui et al. 2016). Supply chain issues related to chip acquisition persist globally, particularly due to the dependence on several countries for manufacturing (Wu et al. 2022). In addition, UV-C LEDs are produced using rare earth metals, which require careful consideration of sourcing and the sustainability of those reserves in the future (Hull et al. 2019). The effectiveness of UV disinfection has been shown to reduce with increased turbidity levels (Farrell et al. 2018; Adhikari et al. 2020). Finally, UV-C LED disinfection (Figure 5) can be relatively complicated compared to chlorination, particularly with regards to specialized spare-parts and energy sources (Lui et al. 2016).

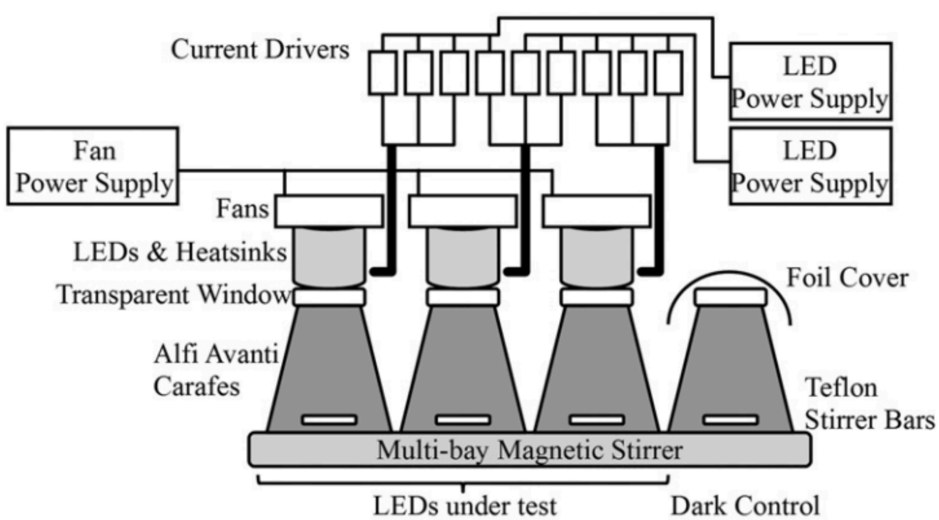


Figure 5: *Experimental set-up of UV-C LED disinfection (Lui et al. 2016)*

2.5 Issues in implementing treatment in decentralized water systems

It is essential that decentralized water treatment technologies are applied successfully, particularly for vulnerable and neglected populations (UN 2015; Amy J. Pickering et al. 2019). The sector holds decades of experience in WASH interventions, but there is a lack of approaches to adapt, scale and sustain access. However, donors and governments are still investing in new technology innovations, "despite compelling evidence that increasing uptake of evidence-based interventions would be more cost-efficient and speed the reduction of health disparities" (Woolf and Johnson 2005; Glasgow et al. 2012). Rather than continuously performing more RCTs or intervention studies, it is crucial that existing studies and interventions are critically assessed under a different lens, namely that of implementation science.

A 2022 critical review of inline chlorination (Lindmark et al. 2022) outlines the key components needed for successful, scalable technologies: electricity access (Linden et al. 2019; Hendrickson et al. 2020), residual disinfection, consistent water supply (Kumpel and Nelson 2016), user burden (Lantagne et al. 2008), local manufacturing/production capacity, and cost of technology and operations & maintenance (O&M). While the review synthesized evidence on the effectiveness of technologies, it identified four research priorities, including i) strengthening supply chains, ii) context-specific financial sustainability, iii) remote monitoring and sensors, and iv) handpump-compatible passive chlorinators (Lindmark et al. 2022). Issues related to supply chains have been shown to limit continued use of PC, as well as creating dependencies on import (Rayner et al. 2016; Dössegger et al. 2021). Financially, few studies show effective demand for PC technologies amongst kiosk owners and landlords (Powers et al. 2021; Smith et al. 2021). Sensor technologies should be prioritized in the future; however, their application in LMICs is relatively uncommon despite their capability to collect and analyze information to maintain and improve long-term service delivery (Wilson et al. 2017; Andres et al. 2018; Turman-Bryant et al. 2020; Thomson 2021). There are limited PC technologies compatible with handpumps; those reviewed are either not capable of providing consistent chlorine dosing (Sikder et al. 2020), or are uncommercialized (A. J. Pickering et al. 2015).

On the UV side, current research priorities are on technological advancements and improving inactivation levels of microbial contaminants (Beck et al. 2018; Hull and Linden 2018; Linden et al. 2019) and developing technologies with decentralized energy supply (Lui et al. 2016). However, the implementation of the technology in full-scale centralized or decentralized water treatment systems remains poorly characterized and understood (Jarvis et al. 2019). Building on these gaps, this study incorporates the identified research priorities within an implementation science framework in order to uncover the requirements for sustainable long-term management of decentralized water treatment systems. Further, there is a poor understanding of the differences and similarities between implementing PC and UV technologies, a gap which this research aims to fill.

3 | Conceptual framework

The following section will describe and explore the conceptual framework of this research, which serves as the foundation for the chosen methods and guides the data analysis. First, the broader basis of implementation science will be explained, followed by the establishment of the RE-AIM conceptual framework within this field. Finally, the RE-AIM framework will be linked to a set of themes aligned with the implementation of PC and UV-C LED technologies.

3.1 Implementation science

Implementation science (IS), also known as translational research, constitutes the "effective translation of the new knowledge, mechanisms, and techniques generated by advances in basic science research into new approaches for prevention, diagnosis, and treatment of disease", in order to reduce the research-practice gap that exists (Fontanarosa and DeAngelis 2002; Nilsen 2015). Originating from health systems science and public health research, IS provides a range of theoretical, analytical and experimental methods in order to gain awareness of what makes interventions successful and sustainable at scale and over time (Glasgow et al. 2004; Madon et al. 2007; Yamey 2011; Brownson et al. 2017; Rosenthal et al. 2017). The foundation of IS seeks "to promote the systematic uptake of research findings and other [evidence-based practices] into routine practice to improve the quality and effectiveness" of certain interventions (Nilsen 2015).

IS uses theories, models and frameworks to achieve its goals of successful interventions, with the following key definitions being applied. Theories are analytical principles or statements that create structure to observations and understandings of the world (Wacker 1998; Carpiano and Daley 2006; Nilsen 2015). Models constitute a "deliberate simplification of a phenomenon or a specific aspect of a phenomenon" that provide value without necessarily being accurate representations (Carpiano and Daley 2006; Nilsen 2015). Frameworks may include structures, overviews, outlines, systems or plans of different descriptive categories and their respective relationships to depict a phenomenon (Frankfort-Nachmias and Nachmias 1996; Nilsen 2015).

The use of IS is aimed at connecting the space between lab findings and efficacy studies, and applying these outcomes to real-world settings, often in public health, nutrition and health systems research (Theobald et al. 2018). IS has been applied in the WASH and environmental health sector, but often under varying labels (e.g. translational research, systems thinking) (Rosenthal et al. 2017; Currie et al. 2018; Neely 2019; Setty et al. 2019; Rosenthal et al. 2020). The application of IS for WASH interventions has recently gained increased attention from several key donors (USAID 2020). Some successful applications of implementation science in WASH have been realized in recent years (Freeman et al. 2017; Wolf et al. 2018; Prüss-Ustün et al. 2019). By focusing on the fundamentals of IS, effective, context-specific, evidence-based solutions may lead to improved "policy- and programmatically relevant questions" (Haque and Freeman 2021). The application of an IS approach to rural water treatment interventions, namely PC and UV-C LED, has not previously been employed and provides a novel understanding of the complexity of systems beyond technical components. Furthermore, using this approach serves to answer RQ1: "What are the main factors that determine the sustainability of implementing treatment in rural water supplies?", where previous studies have focused primarily on short-term effectiveness (Freeman et al. 2017; Wolf et al. 2018; Prüss-Ustün et al. 2019).

3.2 RE-AIM Conceptual Framework

The RE-AIM framework is an IS tool that was originally proposed and developed in 1999 by Glasgow et al. in order to evaluate public health interventions according to five key dimensions, including Reach, Effectiveness, Adoption, Implementation, and Maintenance (Glasgow et al. 1999). Its development was driven by a need to use resources efficiently, align different stages of research, and improve public health practices (Glasgow et al. 1999). In 2020, RE-AIM was adapted to meet the growing focus on long-term sustainability beyond initial implementation stages, and to account for the dynamic nature and complexities of public health interventions (Shelton et al. 2020). The RE-AIM framework is compatible with systems-based and social-ecological thinking, and the modified version is an appropriate lens through which to analyze decentralized water treatment, as these technological interventions must account for the broader systems surrounding them (Shelton et al. 2020). In addition, the recent modifications ensure that health equity and long-term sustainability are accounted for, which are often still lacking in other IS frameworks and theories (Scheirer and Dearing 2011; Wiltsey Stirman et al. 2012; Proctor et al. 2015; Johnson et al. 2019). In addition, the implementation of interventions should be seen as an iterative process, with a continuous focus on sustainability (Shelton et al. 2020).

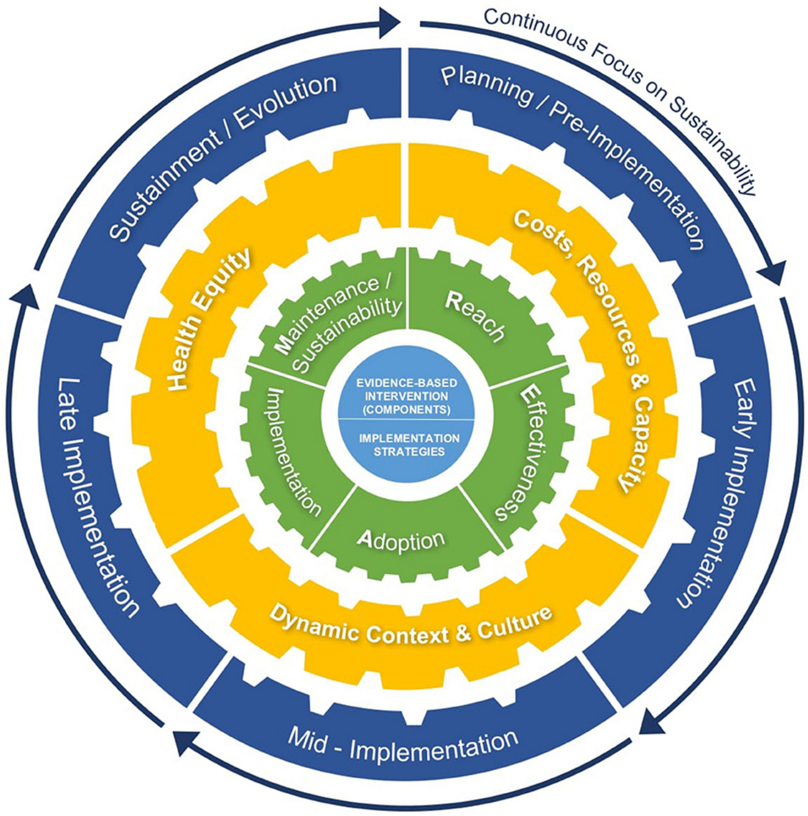


Figure 6: *Updated RE-AIM Framework (Shelton et al. 2020)*

In this study specifically, the five RE-AIM dimensions were mapped onto themes and subthemes related to the implementation of PC and UV-C LED, in order to guide the exploration of facilitators and barriers to successful implementation (Table 2). As seen in the following section, these themes were used as the foundation for the coding component of the qualitative content analysis, and can be categorized as a form of "open coding" (Drisko and Maschi 2015).

Table 2: *Overview of RE-AIM dimensions and thematic counterparts*

Dimension	Description (Glasgow et al. 1999)	Applicability to rural water treatment
Reach	Proportion of the target population that participated in the intervention	Users and customers; collaboration between stakeholders; participatory planning
Effectiveness	Success rate if implemented as in guidelines; defined as positive outcomes minus negative outcomes	Chlorine dosing technologies; dosing/fluence and free chlorine residuals (FCR); UV technologies; water quality
Adoption	Proportion of settings, practices and plans that will adopt this intervention	Communication with communities; perception of device
Implementation	Extent to which the intervention is implemented as intended in the real world	Financing; service delivery models
Maintenance/ sustainability	Extent to which a program is sustained over time	Climate resilience and sustainability; health impacts; scaling up; sensors; supply chain

4 | Methods

The methods section is divided into several parts, including key informant interviews, content analysis, validation of interview findings, systems mapping, limitations of methods, ethical considerations, and concluded with a positionality statement. The study employs a constructivist approach, ontologically, in which it is maintained that social structures and institutions are societal constructs; participants and researchers in qualitative research co-create knowledge (Denzin and Licoln 2005; Drisko and Maschi 2015). This aligns with a systems-based approach, where there are "multiple realities based on peoples' varied interpretative constructs and categories" (Drisko and Maschi 2015).

4.1 Key informant interviews

The method of key informant interviews (KIIs) was selected as a form of exploratory research (Abbott and McKinney 2013: 124) suitably aligned with the RE-AIM framework, to answer RQ1: "What are the main factors that determine the sustainability of implementing treatment in rural water supplies?". The primary method of data collection was through semi-structured interviews with 26 key informants, with interviews ranging from 26 minutes to 1 hour and 45 minutes. The key informants could be categorized as working in academia, NGOs, commercial companies, research institutes, public health institutes, or a combination (Table 3). These stakeholder groups were selected because the bulk of work on these technologies remains experimental, in which researchers are heavily involved. In terms of expertise, 18 key informants were experts in PC and 8 in UV-C LED technologies. Specifically within those technologies, key informants were contacted from a range of technology maturity levels, including established/mass manufactured devices, "build-your-own" devices, and novel innovative design approaches / prototypes. Semi-structured interviews served as a suitable tool for this type of exploratory research, in which interviewees were able to share details of their experiences in a flexible manner, while still being guided by a set of themes.

Table 3: *Number of interviews based on actor category, technology, role, country of organization, and country of operations*

Actor category	**Technology**		**Role**		**Country of organization**		**Country of operations**	
	Cl	*UV*	*Operational*	*Managerial*	*LMIC*	*HIC*	*LMIC*	*HIC*
Academia	5	6	0	11	0	11	8	2
Academia and NGO involvement	2	1	1	2	0	3	4	0
NGO	6	1	4	3	3	4	9	0
Research institute	3	0	0	3	0	3	5	0
Public health institute	2	0	0	2	0	2	1	1
Total	**18**	**8**	**5**	**21**	**3**	**23**	**27**	**3**

4.1.1 Sampling methods

Initially, a number of PC and UV-C LED disinfection projects were identified through connections within the Oxford University School of Geography and the Environment. Beyond these initial contacts, a snowball sampling approach was taken to recruit new interviewees in order to increase the sample size and to locate the most relevant key informants (Abbott and McKinney 2013: 124). Given the connectedness between stakeholders engaging in these two technologies, the snowball sampling approach was deemed most appropriate to be referred to suitable key informants. The main criteria for inclusion in the study were involvement researching or implementing PC or UV-C LED water disinfection technologies in resource-constrained settings. Where possible, multiple stakeholders within the same research or implementation project (varying roles or seniority) were interviewed in order to obtain varied perspectives from respective roles and to cross-check findings from the interviews. The qualitative, semi-structured interviews were continued until thematic saturation was reached, where no new information, including themes and subthemes, are gathered in consequent interviews (Guest et al. 2020).

4.1.2 Interview design and approach

All interviews took place via Zoom, either voice or video, and were audio recorded using a mobile recording device. To provide direction to the semi-structured interviews, an interview guide was prepared and used, structuring the discussions around key themes aligned with the RE-AIM conceptual framework (Appendix 4). Key themes included general facilitators and barriers to implementation, community perception, communication, financing structures, supply chain, measured or perceived health impacts, long-term resilience, and key future improvements. These themes, in turn, were aligned with components of the RE-AIM framework. All interviews were concluded with space for any additional remarks, questions, and queries into potential interviewees to contact. During each interview, detailed notes related to each interview question were written down in order to have back-up information in addition to the audio recordings.

4.2 Qualitative content analysis

Interview audio recordings were transcribed using Trint, an online transcription software. Consequently, all transcriptions were subject to qualitative content analysis in NVivo 12. Qualitative content analysis was the most appropriate method for this exploratory analysis in order to capture the complexity of the surrounding systems of decentralized water treatment technologies (Drisko and Maschi 2015). All interview transcriptions were initially coded to a set of coding nodes categorized by the five aspects of the RE-AIM framework, including Reach, Effectiveness, Adoption, Implementation, and Maintenance / Sustainability. Each of these five components were further separated into subnodes to ultimately classify facilitators and barriers to successful implementation of PC and UV-C LED water treatment technologies. For both technologies, the key findings per RE-AIM category was summarized, and was subjected to a frequency analysis, revealing the number of interviewees mentioning each theme. Several key quotes were analyzed in further detail to reveal the depth of the discussions, and in some cases, conflicting views.

4.3 Validation of stakeholder interview findings

To improve the validity of the findings from the semi-structured interviews, initial findings were stress tested (or 'member-checked') during a meeting with the International Ultraviolet Association (IUVA) SDG Taskforce in order to confirm results and provide further guidance. Additionally, two interviews (one for PC, one for UV-C LED) were carried out one month after completion of general interviews in order to validate the findings from this qualitative research. These interviews were carried out with two original research participants in order to share initial findings to confirm that the conclusions reflected their experiences. Receiving these perspectives on the results of the study offers an additional layer of validity which supports the researcher in addressing their reflexivity (Baxter and Eyles 1997).

4.4 Systems mapping & causal loop diagrams

Through the lens of implementation science, and specifically the RE-AIM framework, it is essential to realize the complexities of the systems surrounding PC and UV-C LED implementation. Thus, RQ2 asks how the factors identified in RQ1 "collectively constitute an enabling environment for safe rural water supply?". To answer this question, two visualizations were produced. First, a conceptual map of categories and key factors (Figure 7) was made using Miro to visualize the results from the coding analysis of the key informant interviews. Then, a systems-based causal loop diagram (CLD) (Figure 8) was created to show the interrelationships between the different thematic (RE-AIM) elements of implementation. Both themes and arrows are carefully labelled and grouped in order to show the positive and negative feedbacks they may have on the successful implementation of decentralized water treatment technologies. CLDs are an effective tool to clearly represent system dynamics in a "flexible, inclusive, and relatively easy to use" manner (Barbrook-Johnson and Penn 2022: 55). However, a limitation of CLDs are that they can be relatively restrictive in their focus on feedback loops and that they put a lot of decision-making power in the researcher's hands (Barbrook-Johnson and Penn 2022: 56). As a result, the conceptual maps developed in this research are presented as conceptual tools that are intended to generate discussion, they are not put forward as full or conclusive representations of the complexity of rural water treatment implementation.

4.5 Limitations of methods

The study was limited by several factors, including the sample size of key informants and time constraints of the research. Particularly, there is a skew towards key informants involved in PC projects (n = 18), as opposed to UV-C LED (n = 8). This however, can be attributed to and is representative of the number of ongoing projects. Similarly, the majority of key informants are professionally based in HICs (n = 23), while most operations occur in LMICs (27 countries) rather than HICs (3 countries). The limitation that arises is that informants are further removed from local contexts. In addition, due to the bulk of the study taking place over the course of 3 months within the summer period, some potential key informants were unable to schedule an interview due to being on leave. Nonetheless, the study was carried out in accordance with principles of thematic saturation.

4.6 Ethical considerations

The University of Oxford Central University Research Ethics Committee (CUREC) approved the research based on the study's CUREC application (SOGE1A2021-031). With respect to ethical research considerations guidelines, all interviewees were sent a Participant Information Sheet before deciding to participate in the interview (Appendix 2). After deciding to take part, all interviewees were asked to return a signed Consent Form prior to the scheduled interview (Appendix 3). All 26 interviewees provided oral or written consent to the interviews being recorded for research purposes, but were pseudonymized in accordance with the information provided on the Participant Information Sheet.

4.7 Positionality

Within qualitative research, it is important to acknowledge inherent biases, particularly related to the positionality of the researcher, which may have an impact on the validity of research findings. In this study, the researcher took an active role in interacting with study participants, possibly influencing the results of the research. Research, as with any other human activities, are subject to failings and mistakes (Norris 1997). I entered this research with no prior academic experience with qualitative research, and therefore utilized existing research and professional guidance to support in the designing of the interviews and research methods. As a white woman currently being educated at the University of Oxford, there were no major obstacles in finding suitable research participants. Further, it is possible that the status of my educational institution may also have resulted in a shift in answers in order to create a desired image of reality, namely through the 'courtesy bias', which is a subset of the 'Hawthorne effect' (Abbott and McKinney 2013). Being aware of this position, I focused on being consistent in the use of my interview guide during all interviews. The use of a snowball sampling approach reduced the researcher's selection bias; however, it may simultaneously reduce access to possible participants outside of those connected groups of people.

5 | Results

The results of this study can be subdivided into three main parts: stakeholder interview findings, visualization of the implementation environment, and an informal validation of the results. The stakeholder interview findings are subdivided into themes categorized by the RE-AIM conceptual framework. Next, these findings are visualized through a conceptual map and a causal loop diagram to reveal the complexity of the implementation environment. The results are then validated through two additional stakeholder interviews to confirm the findings.

The interviews with key stakeholders and informants provided a depth of insight into the implementation of water treatment technologies in resource constrained settings. First and foremost, seven interviews touched on the importance of viewing these technologies within a broader system, rather than in an isolated form. In fact, many barriers are not necessarily restricted by the technology, but instead by the execution of a functional system. Neither UV nor PC should be seen as "silver bullet technologies" and their implementation is "far from simple", requiring extensive consideration of various components, as will be described in the following sections.

5.1 Reach

5.1.1 Users / customers

The customers of UV and PC technologies can range from NGOs, local governments, to individual homeowners, either in the public or private sphere. In order to properly sustain these technologies, targeted engagement with these segments is required. In most settings, the users of these technologies are small communities, schools or healthcare facilities.

5.1.2 Collaboration between stakeholders

A widely held value in both UV and PC projects is the importance of collaborating with other stakeholders, which can range in type and extent. Collaboration with local NGOs is common to employ in-country staff for assistance in addition to remotely located project leaders or researchers (e.g. Get Water Uganda, PATH, SWAP [Safe Water and AIDS], Love City Strong, Helvetas, Maji Safi, CARE). Researchers may decide to collaborate with service delivery companies or implementation partners, as is seen through FundiFix, which is a "a Kenyan-owned and registered social enterprise [that] provides repair and maintenance service for rural water infrastructure serving communities, schools and health facilities" (FundiFix 2021). Commonly, research projects and NGOs collaborate with national entities, including centers for disease research or Ministries of Water. In some cases, the manufacturers of chlorination or UV-C LED products provide in-kind support or implementation guidance; companies include AquaTabs Flo (Medentech), Water Mission, and Aquisense, amongst others. However, some manufacturing companies strictly focus on production and have no interest in branching out into implementation, instead they sometimes collaborate with academic institutes on validating performance and improving product efficacy. Particularly within UV-C LED technologies, there is limited competition with only ~1-2 major companies supplying components or reactors.

Currently, there remains a stark divide between researchers and practitioners within the general field of drinking water treatment. Publications are installations for the purpose of research, and as a result, after ~1-2 years, the scope and/or funding is reached, where projects are brought to a halt. NGOs, alternatively, seek to roll out programs with beneficial interventions to as many people as possible, and thus may not have the capacity for rigorous data collection which is very expensive. Because there are many disparate groups doing different work, there remains an absence of publicly available information about implementation. In addition, there is no formalized community or working group to lead efforts on knowledge sharing; however, 13/18 PC interviewees discussed the importance of collaboration within the sector. The International Ultraviolet Association (IUVA), on the other hand, has a SDG Task Force that meets regularly to share research and practitioners' experiences.

5.1.3 Participatory planning

Although many organizations emphasize the importance of collaborating with local institutions, co-design and participatory planning remains uncommon. However, roundtable discussions and community meetings are relatively commonplace. Alternatively, one interviewee mentioned that co-design was, in fact, not desired because the implementation of drinking water treatment should not affect behavior; this is contrary to principles of participatory planning.

5.2 Effectiveness

5.2.1 Passive chlorination technologies

One interviewee noted that, “we should always do the most centralized treatment that you can possibly do in each context, so if it's possible to do piped treated infrastructure water, we should do that. If that's not possible, we're looking at inline chlorination at the community level, or dispensers at the community level. And if that's not possible, then you look at household chlorination” (Cl_05). While centralized disinfection may not work in resource-constrained settings that deliver intermittent water supply, there is a need for decentralized passive chlorinators that do not rely on electricity and are capable of handling variable flow rates. Compared to ~10 years ago, there are currently many new PC technology options, which are suitable to a wider range of infrastructural settings. Devices are being continually optimized and more efficient, with reservoirs having expanded to treat 20-40k L of water. However, there is still room for product design growth in the coming years, particularly making trade-offs between precise dosing and the complexity of the device.

Because there is a wide range of inline, passive chlorinators, choosing the right chlorinator for the infrastructure in a specific context is essential. In line with this sentiment, “inline chlorinators have a place… but that place is not the entire world” (Cl_05). Examples of infrastructure types include multiple tanks, an overflow tank, or different sized pipes. One particular project is creating a decision tool for households to decide how to select which water treatment to use (Cl_14). T-chlorinators work by being loaded with tablets over which water flows to dissolve the chlorine. Specifically, Water Mission’s 3-inch tablets require less refills than liquid chlorine and act as a permanent add-on in the line as part of the water main. This has high upfront cost, but lower maintenance costs. Alternatively, Medentech Aquatabs Flo’s 1-inch tablets are suitable for a specific range of flow rates and non-pressurized networks. The technology functions using a prefilled one-time use plastic cartridge attached to a tap/tank; once water flows through, the cartridge is removed by breaking it. They are relatively cheap upfront as it is a one-use technology, but ongoing costs are high compared to buying tablets, as the cartridge needs to be repurchased. If there is no supplier, these can be really difficult to procure.

Aquatabs Inline are specifically designed to function in pressurized settings; however, attempts to use install them in non-pressurized settings were very difficult and required multiple plumbers for installation. In addition, one interviewee mentioned the need to drill a hole into the tank prior to installation, which brings added risks to scaling implementation. Self-constructed passive chlorinators are made from generic PVC piping, and are similar to Aquatabs Flo in that the chlorinator is directly attached to a tap feeding into a tank, which can be detached and repaired if needed. Materials are generally widely available and accessible, but some operational challenges, like clogging, may arise. EOS International, Evidence Action and Helvetas have employed this type of chlorinator. Under this category, swimming pool chlorinators (liquid) have been used for decades in continuous-use pressurized pools, and are now being adapted for use in public tanks, which are pressurized.

Inline, passive chlorinators may make use of chlorine in either liquid or tablet form. Liquid chlorine is easily sourced through water guard or other guard products, and bottles of chlorine can be poured directly into devices. Chlorine tablets (solid calcium hypochlorite) work well at the inlet of tanks, are compact, and easily transportable/storable.

The effectiveness of chlorination may vary; in some situations bucket or manual chlorination (like in emergency responses) can perform better than inline or PC. In any case, it is important to strike a balance between low-tech options with high precision. Clogging, due to iron or other deposits, is a recurring issue that can be prevented by having a flushing mechanism in place.

"There's pretty much no technology that works well with handpumps" (Cl_16)

At the moment, there are no effective, commercially available or affordable chlorinators designed for implementation alongside handpumps, with their intermittent pressure being the main issue.

This is a critical development need, as millions of people currently rely on water sources from handpumps connected to boreholes.

5.2.2 UV technologies

At the infancy of UV technologies, UV-C LED bulbs were very expensive and highly inefficient. During the 2010s, the cost had gone down by 100-fold, acting as a major driver for the adoption of UV-C LED technologies. In the lighting industry, Haitz' Law indicates that the development of light efficiency over time follows a logarithmic pattern, where the first few years see barely any efficiency gains due to the many research gaps, and consequent years rapidly increase in efficiency. The primary metric used is dollars per milliwatt/watt of UV power; 10 years ago, devices on the order of 410 microwatts would be incredibly expensive (hundreds of dollars) and last only a couple of hundred hours. However, the past few years have seen the rounding of this development curve, with LEDs becoming more electrically efficient, more powerful, cheaper, and with longer lifetimes, making it slowly become a competitive option compared to other disinfectants. In addition to efficiency gains, UV-C LEDs have triggered a lot of interest because they are compact and contain no mercury, thus offering increased operational simplicity.

There are only few primary manufacturers of UV reactors; however, some stakeholders, in an attempt to make reactors as safe as possible, are focusing on producing devices to monitor flow rates, temperatures, and power supplies. In those projects, one key focus is to have a bypass in case the technology fails, but meanwhile explicitly informing users that the water has not been disinfected.

UV radiation is less effective in turbid waters, due to color content or dissolved matter, as pathogens are shielded. In those cases, similar to chlorination, pre-treatment may be required. Further, dosing is also dependent on flow rates of the water source or supply, which may vary seasonally or geographically. Another consideration for UV disinfection is that many products have not been properly validated or tested against proper performance standards, thus regulations and guidelines should be continuously improved. Because no substance is being "added" to water sources, like with chlorination, it is essential that the water quality is monitored as frequently as possible in order to confirm that UV disinfection is functioning properly. Many respondents consider UV as a "maintenance-free" or "light-maintenance" disinfection strategy. As bulbs are mercury-free, breakages bring lower risks with them. A final point to consider is the last-mile effect: UV disinfection should be installed at the point of dispense, and be treated as a point-of-use (i.e. immediate consumption) technology as it has no residual disinfection capacity.

5.2.3 Dosing/FCR and fluence

For both UV disinfection and PC, correct dosing is a core issue. Specific to chlorine, the majority of interviewees cited the importance not to overshoot concentrations, causing taste/odor issues, or to undershoot, causing recontamination risks. Taste/odor thresholds are below 1 ppm, whereas target concentrations range from 0.2-2.0 ppm FCR at the PoC, in order to have a sufficient residual for 24 hours. The WHO recommends that for water with <5 NTU, the target should be 2 ppm, whereas for water with 5-10 NTU, dosing should be at 4 ppm. For highly turbid waters (>10 NTU), a filter is recommended prior to the doser. Users should be adequately informed about waiting 30 minutes prior to consumption. For water points that use solar pumps, flow rates vary widely depending on changes in the weather; cloudy weather may result in low flow rates and thus difficulties dosing properly.

"Residual disinfection is just an absolute must if recontamination is to be confronted" (Cl_07)

While chlorination offers residual disinfection, there should be adequate information and training on safe hygiene practices, particularly related to containers which often have biofilm sediments, dirt or do not use lids. While it is difficult to disinfect for every use case, major steps are still made towards health improvements.

On the other hand, UV disinfection has no residual effect and is thus only effective as a PoU solution, when directly exposed to water. As opposed to chlorination, it is not possible to easily conceptualize how UV radiation treats water, as nothing is "added" to the water. Therefore, a rigorous way to calculate UV fluence is required in order to consistently inactivate pathogens; this can be done through validation and regulations. UV radiation is relatively agnostic to the taxa of a microorganism as it damages all nucleic acids and proteins, so the overall microbial load is decreased more consistently than with chlorine. Low wavelength UV are very effective at damaging proteins, thus more effective at disinfecting viruses overall; this is a key finding because viruses are thought to be more resistant to UV disinfection. In line with this, UV and chlorine act as complementary disinfection strategies because UV is better at inactivating bacteria and protozoa, while the opposite holds true for chlorine.

5.2.4 Water quality

External variables may have an effect on the quality of source water. For example, heavy rainfall events may cause runoff for hillside springs, and increased contamination from animals or latrines than in the dry season. Rain catchments on roofs are more susceptible to contaminants such as animal feces.

Pre-treatment, either through filtration or absorbent media, is often needed prior to chlorination. In many centralized settings, chlorination is used as the final “polishing” step. However, where PC has been installed, there is often a substantial improvement in water quality. It must be noted that where there is clean water at the tap or collection point, it may not always be safe at the point of consumption. UV disinfection may also require some level of initial filtration for turbidity reasons. Turbidity reduces the efficacy of UV because non-microbial matter (e.g. nitrates, organic carbon) also absorb UV light. As UV is sensitive to the background water matrix absorbance, photons may be unnecessarily wasted without pre-filtration. One study has shown that water was free of E. coli and safe for consumption after treatment. More research is still ongoing, focusing specifically on disinfection compliance (total coliforms, E. coli) and indicators for microbial activity (ATP concentrations, turbidity, water temperature, DBPs potential).

Effective and affordable water quality monitoring is important, in addition to continuous monitoring of the effectiveness of the technologies themselves. Generally, water quality monitoring is carried out by comparing water samples from the tap with samples provided by users from their own sources. The difference between these two samples provides an indication of how the distribution or storage practices impact water quality.

5.3 Adoption

5.3.1 Communication with communities

Amongst the interviews, there was a general consensus that communicating with communities has a positive impact on the implementation of water treatment. Users must know that chlorination or UV disinfection is occurring, and there must be space for them to ask questions or express concerns. If users are not aware of the water treatment methods that are occurring, especially if treatment is not easily visible, they may choose to continue household water treatment methods that may interfere with existing methods. However, there are mixed opinions on whether researchers or external entities should have direct contact with users. Language barriers may hinder effective communication, and in such settings in-country collaborators or partnering companies should take the lead on day-to-day tasks.

"FundiFix were saying that if the people in the community see too many white people, they think that FundiFix are getting a lot of money from the West and they become more reluctant to pay the fee." (Cl_01)

Full community meetings are emphasized, both for the project leads to share information with users or water boards, and for them to ask questions. Water committees, Water User and Sanitation Committees, and Water Boards are quite common, and support in mobilizing attendance from communities. A demonstration component can be beneficial to show devices installation and effective use. Water quality monitoring should be communicated clearly. This can also be used as an entry point to gain trust from users, as an indication of contaminated drinking water may create more buy-in to begin treating water using chlorination or UV technologies. Furthermore, other informational resources may include posters, videos, manuals, education workshops and management trainings. Specifically for UV, education is very important as it is a relatively new technology that is conceptually more difficult to understand. Overall, interviewees were not very specific about how communication or trainings currently occur, but were able to provide indications about best-practices.

5.3.2 Perception of device

Although there are general trends related to the perception of PC and UV technologies, it is of utmost important to emphasize that each community is unique. Additionally, a common misconception of "passive" chlorination is that there is no need for behavior change or sensitization; this is not true, as users are able to switch sources if they are not accepting of their water. The acceptance of passive chlorinators often depends on whether chlorination was being previously performed. For example, existing chlorination practices in some countries in East Africa resulted in fewer adverse reactions to the taste and odor of water treated with passive chlorinators. Similarly, a law in Honduras requires rural communities to treat their water, which is commonly done through chlorination. Issues related to the taste/odor of chlorinated water may be alleviated through focus group discussions and formal blinded tests. One interviewee mentioned that taste buds evolve over time, thus interventions should start at a low dose and slowly increase this. Acceptance may also depend on geographical differences: in piped networks, houses that are closer to the chlorinator may have more complaints about the taste and odor than those located farther away. Besides taste and odor, myths about chlorine tend to be quite prevalent in rural areas, including negative effects on skin, reproductive health, hair loss, or that medication is being added to water sources. In comparison to manual chlorination, PC is generally preferred as the labor burden on users is reduced.

User perception of UV water treatment technologies is still widely unknown; however, there are no issues related to taste or odor. Theft may be a concern if the technologies are seemingly valuable. Beyond users, potential donors must ensure their funds are beneficial, which is currently an issue within UV-C LED technologies due to lacking evidence of measurable, positive impacts.

5.4 Implementation

5.4.1 Affordability

Generally, both technologies offer affordable solutions to water treatment, and do not occur an additionally fee on community members. Particularly in contexts where water is already free, project leaders or researchers are hesitant about adding a fee. This phenomenon may be attributed to the high number of interviewees coming from a research background, as opposed to practitioners' experiences. On the other hand, some key informants mentioned the need for users or communities to have some "skin in the game", to financially sustain water treatment. For passive chlorinators, costs may range roughly from $60-$200 dollars, excluding construction or installation costs. In contexts where users or households do pay a fee, this amounts to ~$1.83 per household per year. There is a common conception amongst interviewees that users "can't afford" the technologies, or that "it's not a priority for people's money", with little evidence to back these claims. Further, in places where the supply chain for chlorine (either tablet or liquid) is not yet established, the operational costs remain too high for chlorination to be a financially feasible form of water treatment. Within operational costs per chlorinator type there are big differences, for example, AquaTabs Flo are not refillable, and cartridges are relatively expensive to replace.

The cost of UV technologies has decreased substantially in the past years, but still varies depending on context and sourcing. For example, an installation in Japan cost ~$1000, servicing a community of 40-50 people. Another reactor (PearAqua Micro) may cost between $20-50. Depending on the scale of projects, UV reactors may see a further price drop; electronics often have a 50-60% discount with increased volume. One study showed that it cost $25 in electricity costs to run the device nonstop for an entire year, indicating that UV technologies have high upfront costs, but low operational costs. LEDs are the main cost driver, which are being reduced substantially with new advancements. Despite this, interviewees still often cite costs as one of the main barriers to successful implementation, even to the extent of being a market premium.

5.4.2 Sources of finance

Initial sources of finance vary widely per project, but are a key aspect affecting long-term financially sustainability. Interviewees from this study, specifically, most commonly acquire funding through research grants, such as the Hilton Foundation, ETH4D, REACH, the Bloomberg Foundation, or other challenge prizes. NGOs collect donation-based support through charities or other organizations. International aid organizations, such as USAID, UNHCR, CDC, or the Swiss Agency for Development Cooperation, as well as national governments, like the Spanish or Swiss, offer financing in the form of development funds. Commercial entities, such as manufacturers, may collaborate on projects by donating devices or refills in-kind. Other sources of finance may come from chlorine sales, water-as-a-service models, or through carbon credits. Because PC is an alternative to boiling water, which is done by burning wood, there is an indirect reduction in carbon emissions. However, carbon credits are not a predictable or stable source of finance, as regulations change on a yearly basis and the verification process can take several years.

5.4.3 Longevity / sustainability of finance

Financing water treatment in small communities remains a larger issue, beyond that of financing PC or UV technologies specifically. Initial sources of funding are often available, but continued financing tends to be difficult. Therefore, creative business models must be developed in order to sustain these water treatment technologies.

> *"There is a struggle in a lot of low and middle income countries to recover enough funds to operate water. And so I would leave this to the economists and the business people. But what I would add is that I don't think there's going to be any one model, models will change by context." (Cl_05)*

In terms of long-term financial sustainability, market-based approaches tend to work well. For example, combining community buy-in with a consistent supply of income (e.g. chlorine sales) has been shown as a successful model. Collaborating closely with communities to ensure they have funds built up over time to accommodate for technological failures or replacement parts further enhances this sustainability. Business models can vary by context, but many interviewees cite the use of hybrid business models, despite this area requiring further research. In-kind support from governments or manufacturers may offer advantages as well. Previous research has shown effective demand by kiosk owners in Dhaka and Kisumu at the community scale to pay for devices through a hybrid model. Finally, the cost of labor, often placed on women and girls, is not often accounted for within financing schemes.

5.4.4 Service delivery models

O&M models must be in place to ensure that the technologies remain functional after the initial implementation. As one interviewee notes, "Inline chlorinators are a system and we need to have systems to maintain them" (Cl_05). Generally, service delivery models can be divided into two broad categories: community led and external / organizationally led.

Community-led service delivery models require upfront training and communication. For UV technologies, more technical expertise may be required. Water committees or boards, consisting of several community members who are responsible for operating the technologies through non-paid positions, are widely cited as an effective mechanism for maintenance. These members are elected to manage the technologies and purchase any replacement parts, or in the case of chlorination, liquid or tablet chlorine. Trainings should be provided at the start of the intervention, and as refresher trainings in consequent years. One disadvantage is that training 4-5 people is more time-consuming than having one expert to manage the technologies. Community-led management can be combined with external management or experts who offer support regarding technical components, funding, or long-term management.

Alternatively, external research bodies, NGOs, or service delivery companies can carry out ongoing O&M. These partners would be in charge of installing and monitoring PC and UV technologies. The Circuit Rider Approach, which involves a series of technicians that have a circuit of ~50 communities, has been an effective mechanism to use technical expertise to monitor the technologies in an ongoing way. By employing local staff, reliance on research partners is avoided and greater cultural understanding is ensured. Within this approach, issues related to fuel shortages must be considered due to the geographical distances. Interviewees emphasize the importance of engaging with the "right" long-term partners, stating that these should either be local bodies (government, NGO), or stakeholders that plan to stay in the community or country for a long period of time. Management bodies must have a vested interest in improving drinking water quality.

5.4.5 Labor burden

Chlorinators and UV reactors require some level of management and accountability, as well as time, resources, transportation, and trainings, which can create additional burdens. Accounting for this labor burden is a challenging task, particularly in resource-constrained or rural settings.

Despite inline chlorination being a more "passive" approach, the labor burden may still be significant. The technology functions as an opt-out way as opposed to an opt-in way, which is how household water treatment works. One interviewee raised that healthcare facilities were very pleased, as there's "one less thing they had to deal with in the day". However, refilling chlorinators remains a difficult task which involves adjusting dosing rates and adding liquid or tablet chlorine every few weeks, either by water committees or external organizations.

UV technologies require less ongoing maintenance as they are consumables-free, but do still require regular quality checks before and after treatment to confirm performance. Interviewees provide mixed answers on the frequency of maintenance, ranging from monthly to semi-annual checks. If pre-filtration or screening is in place, filters must be cleaned in order to prevent biofilm from building up or from turbid waters blocking the screen. The glass or quartz component of the UV reactor must be cleaned regularly, as build-up may prevent the radiation from working properly, resulting in added costs, water, and electricity use. There is a general consensus that UV technologies must remain low-tech and have a user-friendly interface to read and control flow rates.

5.5 Maintenance / sustainability

5.5.1 Emerging contaminants

Climate change will likely alter the quality of source waters by adding new pathogens and contaminants, creating additional difficulties for treatment; however, this remains largely unexplored and is not prioritized in implementation projects. The focus currently remains on maintaining a consistent water supply and the disinfection/inactivation of existing contaminants.

5.5.2 Energy consumption

In the face of climate change, energy consumption and sources of energy will be critical to consider. Inline chlorinators do not use electricity, providing them with a key advantage over alternative technologies. UV, on the other hand, does require electricity, but the energy required is quite modest. Unlike mercury-based UV bulbs, no energy is lost to turning LED bulbs off and on, meaning lifetimes can be extended, and bulbs are appropriate for intermittent demand. With UV disinfection being connected to the grid, there are issues related to power surges or outages (either as an oddity or natural disaster). Self-sustaining UV water treatment, powered through photovoltaic energy, is being developed in research settings. Alternatively, small generators may be a good source of energy in some settings.

5.5.3 Materials

In efforts to scaling up technologies, the material consumption should be considered. UV-C LEDs replace traditional mercury lamps, which reduce ecological and human health risks. With a lifetime of ~10,000 hours, they are more resistant to breakage. However, UV-LEDs are produced with rare earth metals, which may be prone to supply chain risks in cases of geopolitical conflict. Additionally, glass has a high carbon footprint due to the energy required for production. While recyclability of materials are considered, the main drivers of design are economic and technological, rather than environmental. Few interviewees were able to comment thoroughly on the material use of chlorinators. However, it was mentioned that plastic components may start to break down due to being in the sun for extended periods of time. Newer projects are developing devices that will withstand rain and continuous sunlight exposure, while optimizing cost and material availability.

5.5.4 Water supply changes and source protection

Climate change will cause disruptions to water supply and WASH, through the form of more frequent drought, floods, and water-related disasters. Particularly, small island states are more vulnerable to climate change, especially communities that are reliant on rainwater. Variable flow rates pose challenges for chlorine dosing, which is already a challenge in consistent conditions. With heavy rainfall events, turbidity will increase, resulting in both chlorination and UV being less effective. Thus, both technologies should be considered alongside a broader suite of system improvements. While this is important, many key informants shifted the focus towards water treatment rather than discussing the provision of water.

"But we really are focused on the provision of treatment where there is access and less on the provision of the access." (Cl_17)

Similarly, climate change will also have an impact on water quality and a subsequent need for more source protection. People may be driven to use non-conventional sources of water, or focus on water reuse. Source protection, namely the conservation of source water and natural protection against contaminants or agricultural runoff, can be executed through planting trees around the body of water. As this is a relatively long-term solution, increased community buy-in would be required. Other natural types of source protection may include slow sand filtration, the use of activated carbon filters or stone filtration. Again, interviewees generally share that long-term resilience is widely unexplored and seen as a lower priority.

5.5.5 Health impacts

To date, there is very little scientifically measured evidence of improved health impacts due to PC or UV disinfection interventions. One prior randomized controlled trial that took place in Dhaka showed evidence of a reduction in childhood diarrheal disease due to PC interventions (A. J. Pickering et al. 2019). Health improvements have been measured informally in other contexts, showing fewer incidents of diarrheal disease in communities with passive chlorinators compared to those without; however, these were not carried out with the same rigor as RCT counterparts. Most studies related to chlorination do not measure health impacts due to the additional ethical considerations and protocols that are required. On the UV-C LED side, health impact evaluations are still lacking. However, studies using conventional mercury-based UV bulbs may offer insights into health improvements.

Some interviewees provided information on perceived health improvements based on anecdotal evidence. This anecdotal evidence widely indicated a reduction in stomach cramps. However, there are many other confounding variables that have an impact on human health, making it difficult to pinpoint how PC or UV disinfection specifically have an impact. Further, the belief that water treatment is important or beneficial to health may also have an impact on the incidence of disease. One informant shared that transitioning from boiling water to alternative water treatment methods with less impact on air quality also serves as an improvement to health.

Disinfection by-products (DBPs) are a risk posed specifically by chlorination practices; these are produced when disinfectants react with inorganic or organic matter. To minimize these risks, regulations must be put in place and enforced in a way that health benefits can still be reached with chlorination. This will require a balancing act between concentrations that are low enough to minimize the risks from DBPs, but high enough to minimize the risks from microbial contamination.

5.5.6 Sensors

In most communities with decentralized water treatment, there are many technicians or circuit riders visiting regularly for consistent monitoring. The development of sensors allows for prioritization of visits, and thus more efficiency in maintaining functional water treatment. An alert will arise, indicating that a visit should be made to a particular community. Within this research, the goal should be towards live monitoring of chlorine levels / UV fluence levels, in addition to live water quality monitoring. Currently, ORP sensors are being used as a proxy indicator. UV transmittance sensors should be incorporated in order to make technologies more responsive and to select options based on changing source water quality.

5.5.7 Supply chain – Chlorine

Chlorine supply chains present many issues in the implementation of PC, on a global scale. Chlorine comes in the form of liquid or tablets, where liquid chlorine can easily be locally sourced or produced, and tablets usually need to be imported, unless supply chains are locally established.

In addition, chlorine tablets have a higher concentration and are easier to transport, but are only produced in very few countries. For example, all Aquatabs / Medentech products are made in Ireland. Having few producers results in a highly vulnerable, fragile supply chain dependencies. While some interviewees were protective about providing specific names of manufacturers, it was found that there are only three primary chlorine suppliers in the US, and one of these experienced a fire resulting in major chlorine shortages. An additional operational issue is that tablets cannot be flown due to their hazardous nature; this poses major challenges, particularly for humanitarian crises.

"There's a tension between chlorine tablets that use a higher concentration of chlorine, you need less of them, they're more consistently produced but you must import them, versus local [liquid] chlorine which can be really tough." (Cl_05)

While supply chains are generally a common issue, components besides chlorine are easily to source locally. PVC pipes are readily available, while valves are occasionally more difficult to source. Pre-treatment filters are sometimes necessary to reduce turbidity prior to treatment, to make the treatment more effective. Overall, having multiple complementary technology options makes systems more resilient to supply chain disruptions.

5.5.8 Supply chain – UV

As with PC, interviewees cited many supply chain issues related to UV products. Electronics, specifically microchips, come from very few places, including China, Taiwan, and Korea. This creates further geopolitical dependencies and vulnerabilities for countries that depend on importing these products. However, informants often mentioned that if economic advancements could be made, it would be possible to source locally which would be preferred. Specifically, COVID was often mentioned as causing major disruptions to supply chain, preventing smaller projects from being able to source necessary materials. One interviewee emphasized the importance of having all components be replaceable locally, especially from a humanitarian standpoint. This is a sentiment that not only holds true for UV disinfection, but for all water treatment technologies implemented in small, resource-constrained settings.

Table 4: *Summary of results from key informant interviews*

	Theme	Description	Quote(s)	Average % of interviews coded to theme	Range of % coded to theme	Number of interviews discussing theme
SYSTEMS	Systems approaches	Relates to the interconnectedness of the components of implementation and viewing them in relation to each other	"Well, I mean, first thing that comes to mind. With any technology, including chlorine, these aren't silver bullet technologies." (UV_04)	0.98	0.43-2.40	7
REACH	Users / customers	Relates to who the customers and/or users of the technologies are	"The customers could be NGOs that are partnering with healthcare facilities or the local government that is providing water at schools and other institutions. It could be individual homeowners. It could be private. The device itself could work in a lot of settings. So I think it's going to be kind of a wide range of customers." (Cl_04)	1.54	0.85-2.27	5
	Collaboration between stakeholders	Relates to how various stakeholders, including industry, research, implementers, NGOs etc., collaborate with each other to improve implementation practices	"I feel like there's a couple of bad eggs that like are not about collaboration. It's all about touting their best design and their best approach. But a lot of us on the other side, we're connected. ... You know, we love information, we have a lot to share, but we learn as well." (Cl_18)	3.40	0.41-9.68	19
	Participatory planning	Relates to how involved end-users are in the implementation process, from start to finish	"I feel like really starting with engaging the community you've actually impacted and using participatory research methods where you are actively conducting needs assessments or asking the community to work on the research in terms of designing experimental studies or the actual implementation plan." (Cl_04)	0.98	0.33-2.15	4
EFFECTI VENESS	Chlorine dosing technologies	Relates to the effectiveness of chlorine dosing technologies and their development	"You can't say inline chlorinator A is going to be the same as B, they could be completely different products. So I think understanding products that provide more consistent quality dose is really crucial." (Cl_05)	6.95	1.39-15.78	14

	UV technologies	Relates to the effectiveness of UV disinfection technologies and their development	"LEDs have sparked interest, and I think that's spurred more interest in implementation and also advances in solar power as an option for powering UV systems." (UV_04)	7.55	3.69-14.69	6
	Dosing/FCR or fluence	Relates to issues and goals in either dosing chlorine accurately and maintaining UV fluence accurately	"I think one of the biggest barriers we have is the difficulty of ensuring a consistent chlorine dose with inconsistent flows of water." (Cl_05)	5.20	0.55-17.10	22
	Water quality	Relates to pre-treatment water quality issues	"I think what would make sense if you have higher turbid water or other chemical or biological contaminants would be to pre-treat the water that is coming in." (Cl_04)	4.71	0.96-16.90	18
ADOPTION	Communication with communities	Relates to how project leaders communicate and engage with end-users during the implementation process	"I'm very adverse to having some outsider come tell you what you need so if you can have people established in that community, working alongside community members. That's the only way, the best way, to engage and exchange knowledge on those types of opportunities." (Cl_14)	4.87	0.33-9.07	24
	Perception of device	Relates to how end-users perceive the water treatment devices and key factors required for user acceptance	"It is assumed that passive chlorination avoids or removes the need for any behavior change or user sensitization. 'You don't even need to worry about educating people. All these issues we had with point of use treatment, you don't have to worry about that. People will just get that water period.' Well, that's not true. First of all, if people are unhappy with you putting the chlorine, you know, forcing them to get chlorine, they can switch sources. They can go to a very polluted source because they dislike your chlorine. And myths about chlorine are very prevalent in rural areas. In Uganda, for example, it is common to believe that it leads to fertility issues. So you do need to kind of counter those beliefs. And so you don't remove the need for community sensitization." (Cl_11)	6.47	0.27-12.43	25

IMPLEMENTATION	Financing (affordability)	Relates to the affordability of passive chlorination and UV technology products, including consumables (if applicable)	"I think that's the biggest challenge, really, is if you want to make it financially self-sustainable. How do you do that? People can't afford it basically. Or if it's not priority for people's money." (Cl_01)	1.90	0.52-5.87	19
	Financing (longevity/ sustainability)	Relates to the long-term sustainability of financing required to manage ongoing operations and maintenance of the water treatment, including business models	"I mean, I hate to keep repeating myself, but I think it really sort of comes back to the education, economic issues and business issues. I think those are really the biggest barriers." (UV_09)	5.94	0.64-32.56	24
	Financing (sources)	Relates to the initial and ongoing sources of financing	"So donor money going into other countries to provide technology that they didn't build. Kind of the quintessential development approach." (Cl_14)	3.52	0.78-10.46	20
	Service delivery models (community vs organization)	Relates to the operations & maintenance models applied in the implementation of these water treatment technologies	"You really need some sort of outside organization support for the maintenance of these chlorination technologies or, you know, whether it's just having some sort of technical support, like to consult if something goes wrong to help, you know, maintain the supply chain, get replacement parts, either some local NGO or just as much more buy in from local governments is something that I think is going to be required." (Cl_02)	5.48	0.41-20.12	17
	Service delivery models (labor burden)	Relates to the distribution of labor for ongoing maintenance and management, specifically who carries the largest burden	"Whether you're talking about household community, institutional utility, if you assume that the users are going to take ownership and maintain the system on their own, you might be ignoring a large part of the financial and time and cost burden which are often gendered, that are associated with this long term operation and maintenance. And figuring out that piece, especially in dense urban or more sparse rural settings and more resource limited areas, is quite challenging." (Cl_04)	4.40	0.90-16.20	19

MAINTENANCE / SUSTAINABILITY	Climate resilience and sustainability (emerging contaminants)	Relates to emerging contaminants that affect source water quality and how this alters implementation	"Climate change is a challenge because it changes the quality of our source waters. And that can make it harder to treat them. It can add new pathogens or new contaminants to the water that old UV systems are not designed to handle. And so monitoring of source of water and monitoring of the performance of UV systems against those sorts of waters, I think will be important." (UV_04)	1.18	0.26-1.65	3
	Climate resilience and sustainability (energy consumption)	Relates to the energy consumption of passive chlorination and UV technologies	"When you have to get a bit more creative in remote regions, then it gets complicated." (UV_04)	1.37	0.28-2.78	10
	Climate resilience and sustainability (materials)	Relates to the material use of these technologies, particularly with regards to recyclability, lifetime, and scarce materials	"A big consideration, especially for UV-LEDs is that they are made of fancy rare earth metals. And I don't know the distribution of where those are located and geopolitical conflicts that might or might not prevent access to those reserves in the future. Just mining them in general is not that sustainable." (UV_08)	2.94	0.26-13.11	10
	Climate resilience and sustainability (water supply changes & source protection)	Relates to the effect climate change will have on future water supply and how this must be managed effectively	"So, you know, I think we're, you know, we're gonna see more and more WASH related challenges with climate, flooding, for example, or drought. I mean, it's weird because it's kind of at the extremes." (Cl_15)	2.98	0.13-8.17	18
	Health impacts	Relates to the measured and perceived health impacts of water treatment, with a specific focus on the risk of DBPs	"There's a lot of confounding variables, because it's it is very hard just to put this technology in and then walk away and let is run. It definitely has to be a systems approach for the technology to succeed at all. So then if there is a decrease in disease, it's attributable to both the technology but also the system that has been created." (Cl_03)	3.69	1.44-8.09	40
	Sensors	Relates to the development of water quality sensors in order to monitor water treatment functioning	"I mean what would be very nice and what is also in development by several organizations is on the sensors side, online monitoring of the chlorine concentration." (Cl_08)	4.15	0.43-4.92	5

	Supply chain (chlorine)	Relates to the supply chain of chlorine(-related) products	"The biggest issue is the supply chain of convenient, easy access to the chlorine consumables." (Cl_02)	8.12	0.63-15.19	19
	Supply chain (UV)	Relates to the supply chain of UV reactors	"Supply and demand is always an issue. At the moment, we're facing a chip shortage worldwide, so the balance of system costs are going up again and perhaps are becoming another difficulty." (UV_01)	5.03	0.97-13.18	9
	Supply chain (water quality monitoring)	Relates to the supply chain of water quality monitoring supplies	"I had found it challenging in the past to work in certain places if I don't have all of the equipment and reagents with me. And so I think that's the part that needs to get figured out as well – how to make affordable water quality monitoring" (Cl_04)	2.51	0.85-4.02	4
	Supply chain (other)	Relates to the supply chain of other components, such as PVC piping, valves, connectors, etc.	"We let's say pushed to most which were the locally, locally built chlorinators, I mean the parts are quite easily available. Sometimes they had to go to the capital to get parts, but most of them were available on the local markets. So for example, for large valves, they had to go to the capital and some connectors sometimes. Um, but most of the parts are very easily available." (Cl_08)	2.59	0.21-6.62	15

5.6 Conceptual visualization map – implementation environment of passive chlorination and UV-C LED technologies mapped onto RE-AIM

Figure 7 visualizes the results from sections 5.1-5.5 as an iterative cycle of the RE-AIM implementation framework. Within this cycle, all thematic elements (nodes) previously discussed are linked to a component of RE-AIM. Further, the key categories, factors and outcomes are linked to each theme. The framework is by no means exhaustive, but offers an initial representation of the complex systems surrounding PC and UV-C LED technologies.

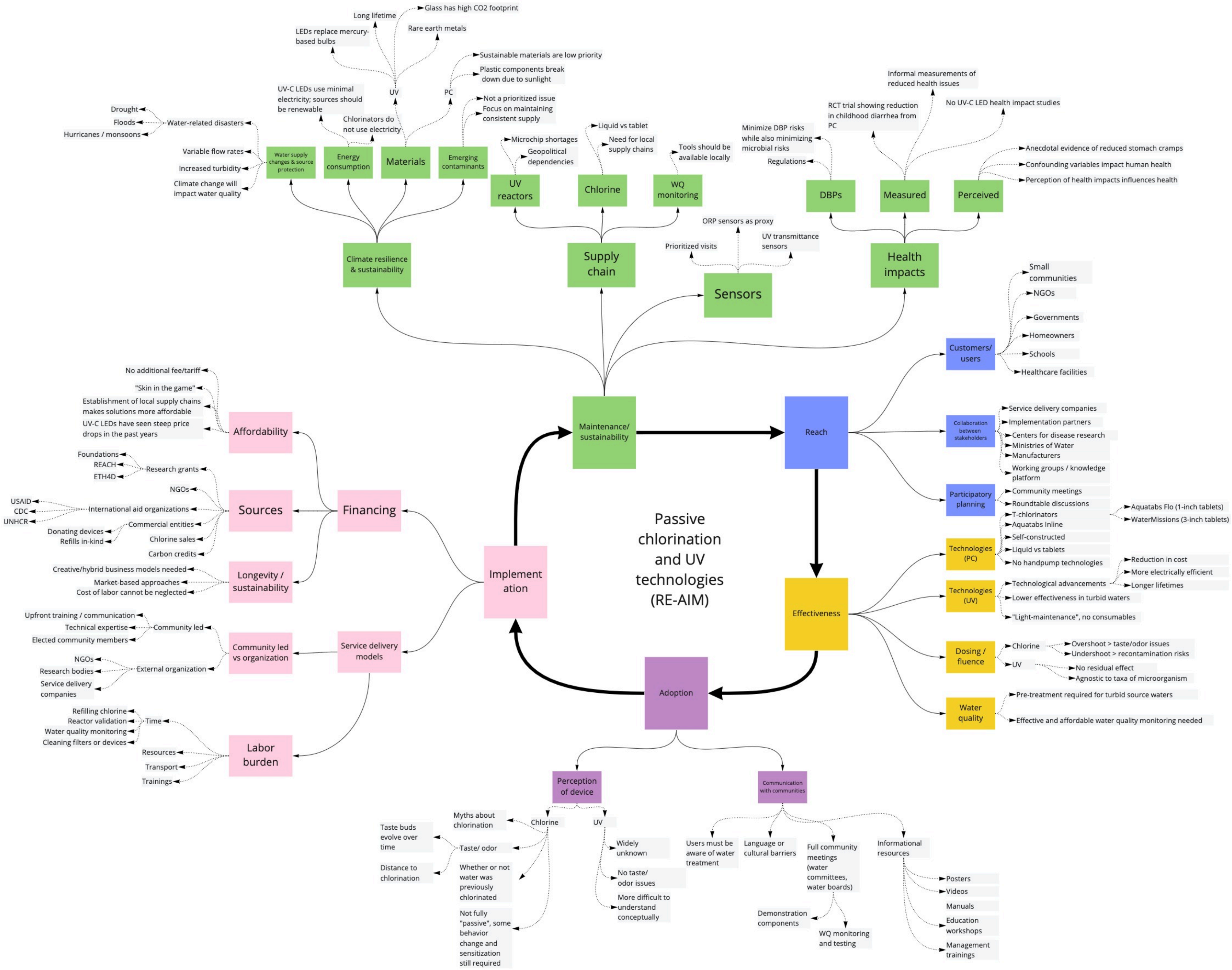


Figure 7: *Conceptual visualization of key categories and factors in implementing passive chlorination and UV-C technologies*

5.7 Causal loop diagram – feedback loops within the implementation environment of passive chlorination and UV-C LED technologies

CLDs are a form of systems mapping that involve boxes, connections and loops to indicate reinforcing (positive) and balancing (negative) feedbacks in a system (Barbrook-Johnson and Penn 2022: 48–49). Figure 8 presents a CLD of the implementation environment of PC and UV-C LED technologies, where the connections and boxes are color coded according to the five components of RE-AIM: Reach, Effectiveness, Adoption, Implementation and Maintenance/Sustainability. Further, positive and negative feedback loops are indicated by '+' and '-' symbols, respectively. The CLD shows how key factors interact with one another, and similar to Figure 7, provides an initial representation of system feedbacks; more factors and connections exist, but these were noted as the most commonly and consistently mentioned from the qualitative content analysis.

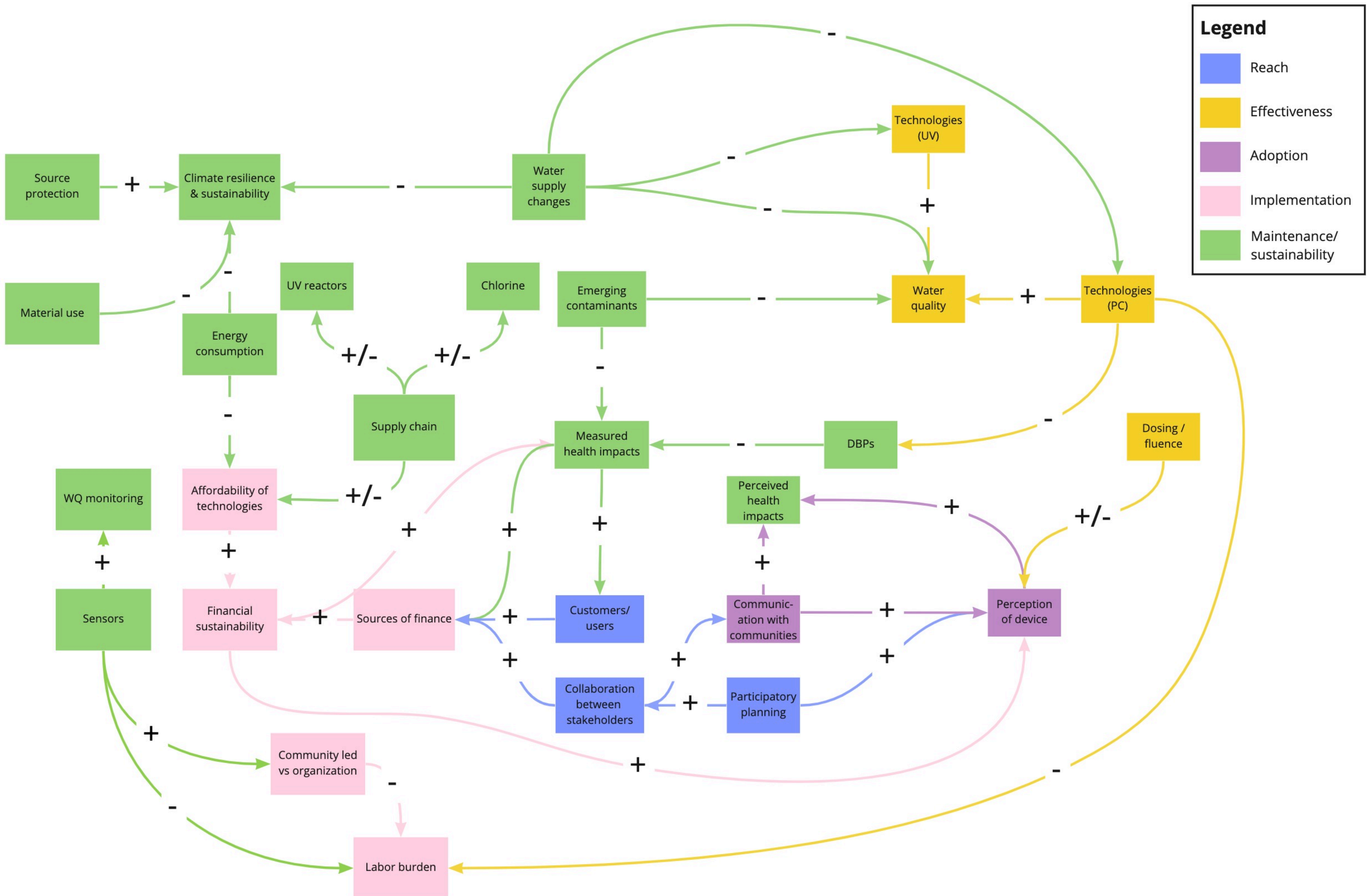


Figure 8: *Causal loop diagram of implementation environment of passive chlorination and UV technologies*

5.8 Validation of stakeholder interview findings

Initial findings were informally stress tested during a working group meeting with the International Ultraviolet Association (IUVA) SDG Taskforce. Task force members confirmed the shortlisted themes, noting that no major components were missing. One month after completing interviews, finalized results were discussed with experts in two separate interviews, one for PC and one for UV technologies. During the interview with a PC expert, several key questions were asked regarding the global geographical spread of chlorine use, and the comparison between supply chains for chlorination and UV technologies. Overall, they found that the results included all key topics, including more that they had not originally thought of. They found the systems map a useful tool to visualize the implementation of PC.

The chair of the IUVA task force provided feedback and validated the findings from the results focusing on UV technologies. They noted that some improvements in water treatment mentioned here are not necessarily unique to UV technologies nor resource-constrained settings, but in fact should be considered in all small-scale water supplies. In addition, while collaboration between manufacturers, researchers and implementers creates increased transparency, manufacturer research is often proprietary, limiting its application in other settings. At present, governments often have regulations for water treatment standards that are based on chlorine-based water treatment, which limits the capacity for UV development. An important query arose with regards to financing; this research involved key stakeholders mainly from a research background, which has resulted a skewed representation of sources of finance towards research grants. Finally, the shift from mercury-based bulbs to LEDs leaves room for further implementation research, while lab-based studies have shown improvements in lifetime and cost effectiveness.

6 | Discussion

The results section has sought to answer the first two research questions, as seen below.

RQ1: What are the main factors that determine the sustainability of implementing treatment in rural water supplies?

RQ2: How do these factors collectively constitute an enabling environment for safe rural water supply?

The discussion first explores key priorities for implementing decentralized water treatment that have arisen from the research findings, to answer RQ3. This takes the form of several sector-wide and technology-specific improvements.

RQ3: How consistent or variable is the enabling environment with respect to different technological approaches?

Then, the dissemination of these research findings and the impact of this study are briefly outlined. Finally, study limitations are summarized alongside potential areas for future research.

6.1 Priorities for implementing decentralized water treatment

In the implementation of both PC and UV technologies, there is room for improvement and some key areas for research and policy focus. Within projects focusing on “development”, there are critical issues related to development funding, and the disparities that arise when considering short-term versus long-term water treatment solutions (Van Houweling et al. 2017). Further, local partnerships and contextualized solutions must be prioritized in all settings (Korff et al. 2012). The mobilization of resources in small water supplies bears interesting contrasts to other technological developments, which should be duly noted. Finally, knowledge sharing is currently lacking in these areas, and such improvements can allow for more (geographically) widespread effective implementation. Specific to PC, more research should be carried out about matching the correct type of chlorinator to existing infrastructure types, as well as on the development of a chlorinator that works effectively for handpumps (Lindmark et al. 2022). In the UV-C LED space, increased awareness, improved regulatory spaces, and more research on the implementation of UV technologies will be critical for scaling up its use (Hull et al. 2019).

Development projects are often deployed in low- and middle- income countries, carrying with them issues related to dependencies, inconsistent funding, and short-term solutions (Fox 2020). This research, specifically, found that research grants and aid organizations were a common source of financing for both PC and UV technologies, rather than revenues from business (models). Issues related to sustainable financing thus arise, leading to the need for economists and businesspeople to support in developing creative business models or financing schemes, which may exist as hybrid models (Machete and Marques 2021). It is essential that whatever type of business model is employed, that this is a circular model in which no external dependencies are formed (Pories et al. 2019). Another key consideration is the establishment of short-term versus long-term water treatment solutions. In this study, some interviewees saw chlorination and UV disinfection as a "bridge" solution, where the more "centralized" water treatment option should always be prioritized. In this light, these technologies are not seen as long-term solutions, yet resources are mobilized in a way to make them so. In fact, decentralized solutions should gain more formalized attention as a valid form of water treatment. This can be done in a number of ways, including engagements with local governments and regulatory improvements (Meierhofer and Landolt 2009; Hull et al. 2019; Smith et al. 2021).

In addition to nuanced critical lenses of development projects, implementation of small-scale water treatment should focus on local partnerships, where solutions are contextualized to specific cultural and geographical settings (Narayan et al. 2020). Although international researchers and institutes play a fundamental role in this space, a shift towards participatory planning and co-design should take place in order to move away from the current us/them dynamic, where project leaders discuss "their" needs and wants without due collaboration (Tsekleves et al. 2022). An interesting contrast in opinions arose around this topic during the interviews, with one informant stating that certain issues "are almost universal in developing countries" and that there are "more similarities than differences" (UV_09). In contrast, another was cautious about making generalized claims, reinforcing that "each community is very unique" (Cl_18). Due care and consideration must be incorporated into the implementation of any form of water treatment, as many socio-environmental components are heavily intertwined, as shown by Figure 8.

The availability of resources, including time, finances, and materials, in small-scale water treatment is limited. Interestingly, parallels between decentralized treatment and space exploration were drawn on several separate occasions. The link between the two sectors is related to their resource-constrained nature; however, space exploration has a much greater amount of capacity, primarily in the form of capital, than small-scale water treatment does. In fact, their commonalities lie in the need for low-maintenance, simple, consumable-free technology which is often limited by supply chains. Poignantly put, "in the case of rural communities, this is cost-driven, while with space exploration, it's logistically driven" (UV_05). Another interviewee shared their frustration with this parallel, expressing the urgent need for the provision of resources in small water supplies, "The tech is there, we put people on the fricking moon and can't figure out how to get people clean water… it's an execution issue that we have, a management issue" (Cl_14). This comparison further exemplifies the financial gap present in the WASH sector, where a lack of sustainable finance will continue to exacerbate the prevalence of short-term, band-aid solutions and continue cycles of dependency on external support (Pories et al. 2019)

A stark knowledge divide exists between various stakeholders implementing passive chlorinators and UV. As previously mentioned, mechanisms must be developed in order to integrate key findings and learnings from research entities and on-the-ground implementers (Theobald et al. 2018). Improved communication will ensure faster progression of best practices and make new interventions more accessible. This may take many forms, including but not limited to: a website, working group / task force, knowledge platform, newsletter, and/or regular meetings. Similarly, innovations in product design should be regularly shared in order to replicate them in different contexts. Both chlorine and UV hold gaps for future research, for which international collaboration will be highly beneficial. Open source information, particularly for the set-up of self-constructed inline chlorinators and UV reactors, must be more readily accessible online (Thomson 2021). Finally, knowledge sharing with regards to systems-based approaches allows for a more holistic design and implementation process.

Within PC research, more research must be done in order to develop a technology that is compatible with handpumps, for which there are currently no commercially available, effective products (referenced 8 times) (Lindmark et al. 2022). A major concern lies in implementing the correct chlorinator depending on the setting's infrastructure, considering flow rates, consistency of water supply, or type of collection (tank, tap etc.) (Dössegger et al. 2021). For this, improved resources should be available to support effective decision-making.

As UV-C LED technologies are relatively novel, more research specific to implementation is required in order to gain trust from end-users, donors, and NGOs in applying the intervention. Similarly, awareness campaigns and the distribution of accessible information may allow for better knowledge on the workings and benefits of UV as a water treatment method. A key development can be made with regards to regulatory standards, which are currently dominated by chlorination as the primary form of water treatment (Hull et al. 2019). Adjustments from a regulatory standpoint could trigger increased attention to advancing UV technologies.

6.2 Research impact and dissemination of findings

As this research is heavily applied and practical in nature, it is important that its findings are shared with relevant stakeholders. Thus far, involvement with the IUVA's SDG Taskforce has allowed for an initial sharing of results. In addition, I was invited to hold a poster presentation on this study at the IUVA Americas Conference between September 26-28; however, I was no longer able to attend due to logistical issues. Fortunately, the results of this research will be presented during a side event session at the UNC Water and Health Conference taking place October 24-28, titled "Implementing passive chlorination at scale: strategies for climate resilience, service delivery, and financing". The collaborative session will bring together researchers to discuss this highly important topic. Besides these two conferences, the findings will be shared with interviewees in the form of a policy brief, and possibly extended to a more formalized publication.

6.3 Study limitations and areas for future research

This explorative study has revealed many key findings about the barriers and facilitators of effective implementation of PC and UV technologies. However, some limitations and subsequent areas for future research should be adequately acknowledged.

Firstly, the interviewee group is heavily skewed towards researchers and research institutes (14/26), which poses issues related to "researching researchers" (Wiles et al. 2006). Interviewing more implementers, commercial entities, or end-users would provide a more holistic image of implementation. In addition, many interviewees were involved in development or research projects, which constitutes the minority of small rural water supplies; instead, municipalities or local governments, which manage the majority of water systems, could provide deeper insights into broader geographies.

Next, some interviews were with people who were yet to begin their intervention projects, or were involved in minimal implementation work. In future research settings, with a larger sample size, a distinction should be made between the results of interviews based on the stage at which the intervention has occurred (i.e. not yet started, ongoing, or started and failed). Nonetheless, determining an appropriate sample size is highly complex and depends on representativeness, which again is difficult to quantify (Abbott and McKinney 2013: 117). The broad geographical scope of this study was suitable for the exploratory nature of the research, particularly due to the narrow technological scope. However, in the future, more granular, geographically focused data would allow for mapping of decentralized water treatment devices to show progress over time.

7 | Conclusion

This research demonstrates the complexities surrounding the implementation of decentralized water treatment in resource-constrained settings, looking specifically at PC and UV-C LED technologies. Access to safe drinking water, as a human right, must be improved globally in order to strive towards the SDGs and to reduce social and economic inequalities. Despite the technologies themselves being effective in removing microbial contaminants from drinking water, their successful implementation is dependent on a broader set of factors. Specifically, key facilitators include long-term financing / sustainable business models, a locally established operations and maintenance model, locally established supply chains, and active collaboration / communication with users or communities. On the other hand, barriers include continued sources of finance, unaccounted-for labor burdens, issues related to community acceptance, and global supply chain disruptions. While general conclusions can be drawn, it is essential that all communities and subsequent water treatment solutions are adequately contextualized. The complexity of all systems must be maintained in order to ensure the long-term sustainability of decentralized, small-scale water treatment.

Existing and future projects must emphasize local partnerships and collaborations with communities. Critical lenses should be taken with regards to development projects and funding, in order to prevent issues related to the short-term nature of many interventions. Because resources are often limited, creative O&M and business models should be developed. Collaboration between researchers and implementers/practitioners should be enhanced to avoid reinventing the wheel and to share experiences. Specific to this study, future research could explore the implementation of water treatment in narrower geographical contexts in order to uncover more specific facilitators and barriers. Additionally, more of an emphasis can be taken towards interviewing practitioners rather than researchers, in order to gain operational perspectives.

Taking a siloed approach to decentralized water treatment, solely through a technological lens, will result in failed projects and stranded assets. To avoid this from happening, systems-based approaches successfully reveal the broader, socio-environmental factors of implementing water treatment technologies and the feedback loops within them.

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Appendix 1: Formal interview request email

Dear [name],

I hope this e-mail finds you well. My name is Merel Laauwen and I am currently doing an MSc in Water Science, Policy and Management at the University of Oxford. In partial fulfilment of the requirements for this degree, I am writing a dissertation about the **implementation of passive chlorination and UV systems for water treatment.** The purpose of the study is to profile the supporting environment, including barriers and facilitators, of in-line chlorination and UV disinfection systems.

I have reached out to you because of your involvement in [passive chlorination / UV-C LED] systems. Ideally, I would appreciate a short interview to gain insights from you about your experiences. **Would you be available to schedule an interview, ranging from 30 minutes to 1 hour, in the next week?** I have attached an information sheet to this e-mail, which contains more details about the research and interview process.

I would be happy to answer any questions in the meantime, either via e-mail or phone call. I look forward to your response!

Best wishes,
Merel Laauwen

Appendix 2: Participant Information Sheet

PARTICIPANT INFORMATION SHEET

Rural Water Treatment Barriers and Opportunities: An Implementation Science Analysis of Chlorine and UV Disinfection in Small Water Supplies

Central University Research Ethics Committee Approval Reference: SOGE1A2021-031

I would like to invite you to take part in our research study. Before you decide whether to take part, it is important that you understand why the research is being done and what it would involve for you. Please take time to read this information. If there is anything that is not clear, or if you would like more information, do not hesitate to ask.

What is the purpose of the study?

The research aims to provide insights into the barriers and facilitators to implementing passive chlorination systems, which can then be translated into possible action plans, further research opportunities or policy reviews. By uncovering barriers to implementation, changes can be made in existing systems or supporting environments to increase access to safe drinking water services.

What are the possible benefits of taking part?

All participation in the study is entirely voluntary and will not be monetarily compensated. By taking part in this research, you will contribute to sharing insights into the supporting environment of implementing passive chlorination and UV disinfection, which can be translated into concrete actions in the future. A summary of the research results will be shared with you, which hopefully provides beneficial findings.

Why have I been invited?

You have been selected as a candidate for interviews as you possess expertise in the area of passive chlorination/UV disinfection or are involved with ongoing projects and research.

Do I have to take part?

No, taking part is entirely voluntary. You can choose to withdraw yourself from the study, without giving a reason, by informing us of your decision. The deadline by which you can withdraw any information you have contributed to the research is 01/09/2022. After this date the dissertation will have been submitted for review.

What will happen to me if I decide to take part in the research?

If you take part in this research, you will be interviewed by the project's researcher, Merel Laauwen, for between 30 minutes and 1 hour. Interviews will be held online, via Zoom. You can expect to be asked a range of questions about following topics related to the passive chlorination project you are involved in: your role and experience, successes, challenges, financing, community involvement, supply chain, health impacts, and data collection. Prior to the interview, you will be asked to sign a digital consent form. This consent form includes a component on consent to audio recording of the interviews for the purpose of transcription, but is entirely voluntary.

Data collection, protection and storage

Audio recorded interview material will be collected and stored as part of this research. Identifiable data (including consent forms) will be stored online using Nexus365 OneDrive, which has been approved by the University of Oxford's Information Security team for the storage of research data.

While the project is ongoing, the researcher and her supervisor will have access to the research data. Your personal information will be pseudonymized by replacing names or other identifiers with a reference number. Responsible members of the University of Oxford may be given access to data for monitoring and/or audit of the study to ensure that the research is complying with applicable regulations. If you choose to consent to audio recording, all recordings will be deleted upon completion of the research.

Researchers will preserve and provide appropriate access to their research data supporting outputs after the end of their project for as long as it has continuing value, in accordance with legal and paying due regard to discipline norms and cost.

The University of Oxford is the data controller with respect to your personal data, and as such will determine how your personal data is used in the study. The University will process your personal data for the purpose of the research outlined above. Research is a task that is performed in the public interest. Further information about your rights with respect to your personal data is available at https://compliance.admin.ox.ac.uk/individual-rights.

What will happen to the results of this study?

The findings from the research will be included in a dissertation for the partial fulfilment of requirements for the MSc in Water Science, Policy and Management. Participants will not be identifiable from these research outputs.

A copy of the dissertation will be deposited in print and online in the Oxford University Research Archive where it will be publicly available to facilitate its use in future research. If desired, this final dissertation can be shared with you. In addition, a one-pager outlining the results of the research will be developed and shared with you.

Who has reviewed the study?

This study has been reviewed and has received ethics approval from a subcommittee of the University of Oxford Research Ethics Committee. (Ethics reference: SOGE1A2021-031).

Who do I contact if I wish to share a concern or complaint?

If you have a concern, please feel free to contact Merel Laauwen (merel.laauwen@bnc.ox.ac.uk) or Saskia Nowicki (saskia.nowicki@ouce.ox.ac.uk) via e-mail and we will respond promptly.
If you wish to make a formal complaint, please contact the Chair of the Research Ethics Committee at the University of Oxford (ethics@socsci.ox.ac.uk) who will seek to resolve the matter as soon as possible.

Further information and contact details:

If you would like to discuss the research beforehand or have any further questions afterwards, please contact Merel Laauwen by e-mail at merel.laauwen@bnc.ox.ac.uk.

Thank you for reading this information.

Appendix 3: Participant Consent Form

PARTICIPANT CONSENT FORM

Study Title: Rural Water Treatment Barriers and Opportunities: An Implementation Science Analysis of Chlorine and UV Disinfection in Small Water Supplies

Purpose of the study: To profile the supporting environment, including barriers and facilitators, of passive, in-line chlorination and UV disinfection systems

Central University Research Ethics Committee Approval Reference: SOGE1A2021-031

Name of Researcher: Merel Laauwen

	If you agree, please check each box
1. I confirm that I have read the information sheet for the above study. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily.	
2. I understand that my participation is voluntary and that I am free to withdraw without giving any reason, and without any adverse consequences.	
3. I agree to the interview being audio recorded.	
4. I understand that research data collected during the study may be looked at by designated individuals from the University of Oxford where it is relevant to my taking part in this study. I give permission for these individuals to access my data.	
5. I understand that this project has been reviewed by, and received ethics clearance through, the University of Oxford Central University Research Ethics Committee.	
6. I understand who will have access to personal data provided, how the data will be stored and what will happen to the data at the end of the project.	
7. I understand how this research will be written up and published.	
8. I understand how to raise a concern or make a complaint.	
9. I agree to take part in this study.	

________________	________________	________________
Name of Participant	*Date*	*Signature*
________________	________________	________________
Name of Person taking Consent	*Date*	*Signature*

Appendix 4: Interview Guide

Stage	Question	Code
Introduction / general	Can you tell me about your involvement with passive chlorination / UV-C LED projects?	G
	How was the project initiated and how has its progress been?	R / E
	Have you participated in or contributed to research?	G / all
	Do you look to other projects or collaborate with others for inspiration?	G
Facilitators to implementation	What have been the successes of your project?	E
	At this point, what has made it possible to implement passive chlorinators?	E
Barriers to implementation	What have been the biggest barriers or challenges?	E
	What steps have you taken to overcome these challenges?	E / M
Community	What is the community perception of passive chlorinators / UV-C LED systems? (Chlorine only): Specifically, have there been any issues (e.g. taste)?	A / I
	How do you communicate information about these systems to community members?	A / I

Finance	Where does financing of the projects come from?	I / M
	Have tariff structures for community members changed since introducing these systems?	R / I / M
	Do you collect any data on financing structures (e.g. cost, tariffs, maintenance)?	R / E
Supply chain	(Chlorine only): Where do you get chlorine from? How consistent is your supply?	I / M
	What are the most important parts you require for maintenance and upkeep? How consistent is your supply of those parts?	M
	Do you monitor any data related to supply chain?	M
Health	Do you think the systems have positively contributed to improved health in the community? How?	E
	Do you monitor any health-related data?	R / E
	How is recontamination avoided? (From containers)	
Long-term	How can long-term (climate) resilience be ensured?	M
Conclusion	What is the one change in the sector that you would like to see in order to make the implementation run more smoothly?	E
	Do you collect any other data that has not been discussed?	G
	With regards to the data discussed previously, is there any data you would be able to share with me?	G
	Is there anything you would like to add?	G
	Do you know of anyone that you think I should speak to in this regard?	G

Appendix 5: NVivo Codebook

Top-level node	Sub-node	Sub-sub-node	Description
Reach	Users / customers	NA	Relates to who the customers and/or users of the technologies are
Reach	Collaboration with stakeholders	NA	Relates to how various stakeholders, including industry, research, implementers, NGOs etc., collaborate with each other to improve implementation practices
Reach	Participatory planning	NA	Relates to how involved end-users are in the implementation process, from start to finish
Effectiveness	Chlorine technologies	NA	Relates to the effectiveness of chlorine dosing technologies and their development
Effectiveness	UV technologies	NA	Relates to the effectiveness of UV disinfection technologies and their development
Effectiveness	Fluence and dosing/FCR	NA	Relates to issues and goals in either dosing chlorine accurately and maintaining UV fluence accurately
Effectiveness	Water quality	NA	Relates to pre-treatment water quality issues
Adoption	Communication with communities	NA	Relates to how project leaders communicate and engage with end-users during the implementation process
Adoption	Perception of device	NA	Relates to how end-users perceive the water treatment devices and key factors required for user acceptance
Implementation	Financing	Affordability	Relates to the affordability of passive chlorination and UV technology products, including consumables (if applicable)
Implementation	Financing	Sources of finance	Relates to the initial and ongoing sources of financing
Implementation	Financing	Longevity or sustainability	Relates to the long-term sustainability of financing required to manage ongoing operations and maintenance of the water treatment systems, including business models

Implementation	Service delivery models	Community led vs organization led	Relates to the operations & maintenance models applied in the implementation of these water treatment systems
Implementation	Service delivery models	Labor burden	Relates to the distribution of labor for ongoing maintenance and management, specifically who carries the largest burden
Maintenance / sustainability	Climate resilience and sustainability	Emerging contaminants	Relates to emerging contaminants that affect source water quality and how this alters implementation
Maintenance / sustainability	Climate resilience and sustainability	Energy consumption	Relates to the energy consumption of passive chlorination and UV technologies
Maintenance / sustainability	Climate resilience and sustainability	Materials	Relates to the material use of these systems, particularly with regards to recyclability, lifetime, and scarce materials
Maintenance / sustainability	Climate resilience and sustainability	Water supply changes & source protection	Relates to the effect climate change will have on future water supply and how this must be managed effectively
Maintenance / sustainability	Health impacts	NA	Relates to the measured and perceived health impacts of water treatment systems, with a specific focus on the risk of DBPs
Maintenance / sustainability	Sensors	NA	Relates to the development of water quality sensors in order to monitor water treatment functioning
Maintenance / sustainability	Supply chain	Chlorine	Relates to the supply chain of chlorine(-related) products
Maintenance / sustainability	Supply chain	UV	Relates to the supply chain of UV reactors
Maintenance / sustainability	Supply chain	Water quality monitoring	Relates to the supply chain of water quality monitoring supplies
Maintenance / sustainability	Supply chain	Other	Relates to the supply chain of other components, such as PVC piping, valves, connectors, etc.