Limitations of Solar Disinfection (SODIS) Water Treatment in Low-Income Communities

By

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Background

Water treatment is a process that has been present in society since 2000 BC; ancient Greek and Sanskrit writings indicate that civilizations were practicing water purification by boiling to improve the taste of their drinking water. It was not until 1676 that scientist Van Leeuwenhoek observed the presence of microorganisms in drinking water, monumental for their rather current basic methods. The London Broad Street Cholera epidemic in 1854 jumpstarted water purification methods, as many scientists aimed to find the root cause and its solution. During this time, methods such as sand filtration, chlorination, and the first instance of government regulation of public water came to rise. With advancements in purification processes, diseases such as typhoid and cholera decreased, and with the public's interest, the Clean Water Act was implemented in the USA in 1972. Beginning in the early 1970's, the public's concern shifted from waterborne illnesses to addressing anthropogenic sources of water pollution as society advanced. Since then, currently used methods such as flocculation, coagulation, adsorption, and membrane filtration have been used to address these concerns, in nations that can prioritize safe drinking water [1].

In many low-income areas, people lack access to expensive water treatment processes such as reverse osmosis and depend on at home water treatment, many times compromising water quality. This is the case for many areas with a lack of access to clean water, where the sources are easily contaminated by sewage, feces, or other harmful bacteria, and are in need of effective water disinfection [2]. Due to fecal and bacteria presence in drinking water, diarrheal diseases have become one of the leading causes of death for children under the age of five in areas without access to clean water. These gastrointestinal viruses cause dehydration, which make those underweight and malnourished more vulnerable. By using Solar Disinfection (SODIS), an effective and cost-free method to disinfect water, viruses, bacteria, and protozoa can be reduced, thereby mitigating negative health impacts [3].

SODIS is performed by filling plastic bottles of any size, in this case 1.5 - 2.0 L full of water, that contain a low turbidity < 30 NTU [4]. Then, the water must be oxygenated or shaken, and placed on an elevated surface such as a roof or in direct sunlight for six hours or longer. If the weather is cloudy, it is preferable to keep the bottles out for up to two days [3]. Advantages of SODIS include the low cost of the system, simplicity of design and use of the system, and proven reduction of waterborne pathogens in the treated water [2]. The system is low cost due to the one-time purchase of plastic water bottles that can be reused, and (free) use of solar rays. SODIS is accessible to all ages due to its simplicity and is very beneficial to those suffering from water-borne diseases, who must prioritize a low-cost but effective system.

System Comparison

Additional water treatment methods targeted for low-income communities include chlorination, slow sand filtration, and ceramic filters. Ceramic filters contain a flowerpot sitting inside a plastic receptacle, usually with a plastic faucet as seen below in Figure 1. A family will fill the receptacle with water which flows through the ceramic filter into a storage area. These filters are proven to be effective against bacteria and protozoa, but not against viruses. Issues often occur when poor quality locally produced filters are used, contaminating the household receptacle with bacteria. The filter needs to be replaced when damaged and requires regular cleaning, especially after filtering turbid water. Ceramic filtration is suitable for regions that can produce high quality ceramic filters where there is a network for part replacement and education on the use and maintenance of the system [5]. This filter has been the basis of Potters for Peace, a United States and Nicaragua based non-governmental organization with an established filter factory, with filters ranging from $7.50-$30, a high initial cost, expected to pay itself back [5-6].

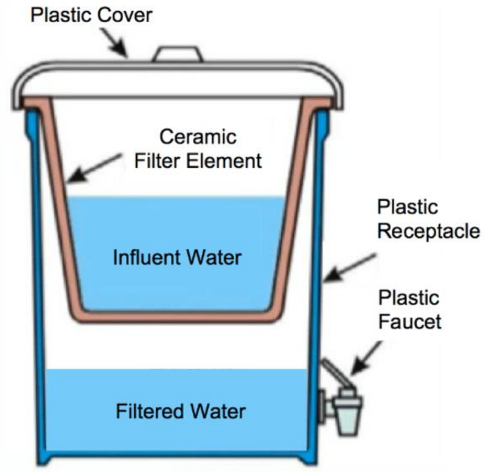

Figure 1. Flowerpot ceramic filter [5]

A sand filter contains layers of sand and gravel in the bottom of a (concrete/plastic) container, allowing the water to trickle through the layers. The goal of sand filtration is to remove suspended solids from the water, as the water passes through the small pores. This is often used in treatment of wastewater, drinking water and swimming pools. Other implementations of this system in action include Samaritan's Purse, Hagar International, and Pure Water for the World [7]. Figure 2 below shows a slow sand filter, and the various layers the water will pass through to become purified.

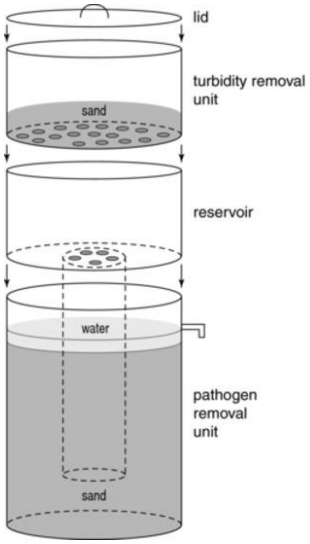

Figure 2. Slow Sand Filtration schematic [7]

Chlorination was a method that was developed in the 1990's as a response to the cholera epidemic in South America by the Center for Disease Control (CDC) and the Pan American Health Organization (PAHP) [8]. Chlorination is the front of the Safe Water System (SWS), providing consumers with a locally manufactured dilute sodium hypochlorite (chlorine bleach, NaOCl) solution. NaOCl consists of sodium salts of hypochlorous acid, with a month-long shelf life due to its corrosiveness and tendency to naturally decompose. The recommended dosage of NaOCl is 0.2-2 mg of NaOCl/L of water treated [9]. Additionally, the SWS provided education on safe storage of treated water and behavior changes to better improve hygiene and sanitation practices [8]. Chlorine inactivates microorganisms by damaging the cell membrane, entering the cell, and then disrupting cell respiration and DNA activity [8].

Table 1. Effectiveness of ceramic filter, sand filtration, and chlorination [10]

	Effectiveness Against *E. coli*	Reduction in diarrheal disease	Flow Rate	References
Ceramic filter	87.6 %	44-47%	1-2 L/hr	[11], [5]
Sand Filtration	80-98%	60-70%	0.6 L/min	[7], [7]
Chlorination	99.99 %	22-84%	Variable	[12], [10]
SODIS	99-99.99 %	9-86 %	1-2 L/bottle	[13], [14]

The data in Table 1 references data obtained by the CDC; they note that their experiments are done in a variety of conditions including both adults and children that may be low-income, living with HIV, or treating highly turbid water [8]. SODIS is proven to be one of the most effective at home water treatments against a common waterborne bacteria *E. coli*, with a disinfection rate of 99-99.99%, with sand filtration having the lowest rate of *E. coli* removal. The reduction of diarrheal disease is dependent on the uptake of SODIS, and adoption into their daily life, therefore producing variable data. SODIS effectiveness depends on a variety of factors such as turbidity, community acceptable, geographical location, and weather as discussed in the limitations section. SODIS does not have a "flow rate" per say because it is not a continuous filtration, but this can be altered due to how many bottles and their size the user decides to disinfect at one time.

Viruses are proven to be the most difficult to eliminate due to their small size, making physical filtration futile. Viruses such as enterovirus, hepatitis A, norovirus, and rotavirus are of concern, and are usually transmitted through human and animal feces [15]. Figure 3 below shows the comparison of at home treatments such as ceramic filtration, solar disinfection, and sand filtration effectiveness at killing viruses.

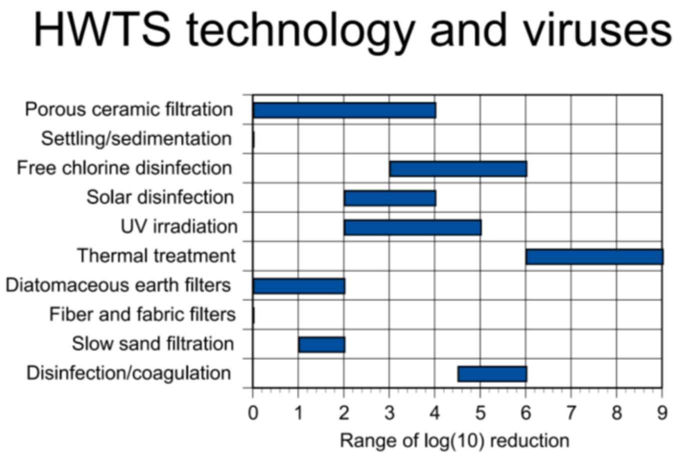

Figure 3. Comparison of home water treatment virus kill rate [16].

SODIS is proven to have higher virus deactivation rate than methods such as slow sand filtration because filtration alone does not inactivate microorganisms. Thermal treatment is seen to be most effective against virus as seen in Figure 3 due to heats deactivating processes and destroying of harmful cells.

Limitations

Although SODIS is proven to be effective in low-income communities with promotional strategies, there are still concerns, attributed to the effectiveness of this method. Concerns regarding the conventional SODIS method include: cloudy weather and latitude, the fear of leaching in plastic bottles, water turbidity and community acceptance [17].

(i) Inclement Weather and Latitude

SODIS is a process that inactivates bacteria through direct solar radiation, which can then be harnessed for drinking water [13]. This mechanism functions by damaging the proteins and DNA of the organisms, induced by radiation in the UV-B, UV-A, and lower visible range. UV-A radiation does not directly affect the RNA or DNA of the pathogens but causes the formation of reactive oxygen species. These species then react with and injure the DNA or proteins of the microorganisms. UV-B radiation inactivates pathogens by degrading microorganisms' DNA or RNA. Heat damages the molecular structure, known as thermal inactivation or pasteurization. The PET bottle absorbs most of the UV-B radiation [13].

At temperatures above 45-50°C, thermal inactivation, and UV-A radiation work side by side to enhance the inactivation rate. With continued irradiation, structural proteins and enzymes are damaged, leading to cell inactivation and death. Overall, cell inactivation is less understood for virus and protozoa than for bacteria. Viruses do not have a cell membrane, meaning the endogenic inactivation process is less important than it is for bacteria. Virus inactivation occurs through the exogenous production of reactive oxygen species. These are mediated through photosensitizers dissolved in the water, damaging the virus's genome. Direct inactivation tends not to occur due to the blocking of the UV-B rays from the PET bottle [13]. Virus inactivation in PET bottles is slower and dependent on water composition. Some protozoa can form cysts or pores that are resistant to solar UV radiation. Most pathogenic protozoa are less efficiently removed by SODIS or require higher irradiation doses[13].

Bottle exposure time is dependent on the location and weather conditions, but areas between 30 degrees latitude North and South are more than 1.3 x higher than the required threshold for SODIS [14]. 780 million people on this planet do not have access to clean drinking water, and ⅔ of this population reside in 10 countries: China, India, Indonesia, Bangladesh, Nigeria, Kenya, and Sudan. Interestingly, all of these are located in the region identified by The Swiss Federal Institute of Aquatic Science and Technology (Eawag)/Sandec as the most suitable regions for SODIS [18]. The recommendation is six hours of exposure on sunny days in tropical countries, but it is advised to have a full day (24 hours) of exposure even with sunny conditions [13].

Table 2. Sunlight Exposure Time Needed Due to Weather Conditions [13].

Exposure to direct sunlight needed	**Cloud Cover**
1 day	50 %
2 days	> 50%
SODIS should not be used	Continuous Rainfall

Table 2 outlines the exposure protocols that should be followed for the most effective microorganism inactivation in days of inclement weather according to Eawag's study. Cloud cover reduces the UV exposure, therefore impacting SODIS effectiveness and increasing treatment time.

A study in Haiti by Oates et.al evaluated whether the SODIS threshold of 3-5 hours of solar radiation above 500 W/m^2 was sufficient for microbial inactivation, year-round. Field measurements began in January of 2001, considered Haiti's coolest month with an average temperature of 25 °C. Deactivation rates of *E. coli*, total coliform, and H_2S producing bacteria were tested before and after radiation exposure. 1.5 L PET bottles were filled with microbial rich water. After one day of exposure, the water bottles experienced microbial inactivation 52% of the time. After 2 days, microbial inactivation was observed 100% of the time. However, if the irradiation was below 500 W/m^2, there was no inactivation recorded, making irradiation level a critical aspect of SODIS efficiency [19]. Haider et al. confirms an intensity of 500 W/m^2 over a period for 2-5 hours/day is necessary for microbial inactivation [18].

(ii) Leaching in Plastic Bottles

A public concern with using polyethylene terephthalate (PET) bottles, is the potential chemical release at high temperatures [20]. Concerns include the health risks that come with plasticizers and carcinogenic compounds that could leach into the water after SODIS treatment. Fears were fueled due to a press report released in 2003 regarding the migration of organic compounds from used PET bottles. Authors in the research published that the plasticizer di(2-ethylhexyl)adipate (DEHA) was present and exceeded acceptable carcinogenic risk levels in the water [21].

A study performed by Schmid et al. explored the transfer of organic substances from PET bottles to water under SODIS conditions. Bottles filled with water were exposed for 17 hours at a geographical latitude of 47° N in Dubendorf, Switzerland between 194 and 845 W/m^2 irradiation, with a total residence time of 48 hours. Using quantitative determination, plasticizers di(2-ethylhexyl)adipate (DEHA) and di(2-ethylhexyl)phthalate (DEHP), were found to have concentrations of 0.046 and 0.71 μg/L. These values lie within the same range of levels of plasticizer in commercial produced bottled water. Toxicological risk assessment determined a minimum safety factor of 8.5 and a negligible carcinogenic risk of 2.8×10^{-7} for the more critical DEHP. This data concludes that SODIS is safe with respect to DEHA and DEHP human exposure [20]. With this in mind, it is still recommended that bottles are replaced every 6 months, to minimize the effects of the wear and tear of the plastic bottle [21].

Montuori et al. (2008) assessed human exposure to phthalic acid and phthalate esters from water packed in PET and glass bottles. The concentrations of phthalates were 20 times higher in sampled PET bottles than the glass bottles. Although there was a concentration prevalent, it was less than 0.1 % of the allowable limit as distinguished by the Environmental Protection Agency (EPA) [22]. This was supported by an additional study by Kamuntu et. al compared SODIS efficacy using glass vs plastic polyethylene terephthalate (PET) bottles. Glass is not subject to photodegradation as PET bottles are more resistant to aging effects. This study was completed under prime and overcast weather conditions at Makerere University in central Uganda. Efficacy was measured by the inactivation of *E. coli* in the water, from a range of conditions: shallow wells, open dig wells, clear and turbid water.

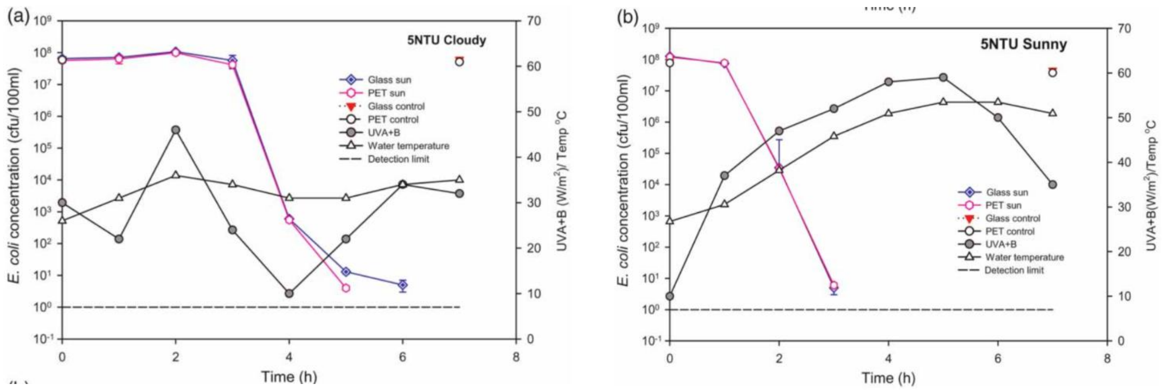

Figure 4 and 5. 5 Turbidity in different climate conditions [23].

Figures 4 and 5 above report the clear 5 NTU water in both cloudy and sunny conditions are almost identical in *E. coli* inactivation. The dashed horizontal line represents the limit of *E. coli* detection 1 CFU/100 mL. Inactivation began after the first hour, and temperature was the same for both materials of bottle [23]. The average UV irradiance and temperature for the experiment was 43.5 W/m^2 and 39.4 °C. The study concludes there is no significant difference between the glass and PET bottles inactivation (95% CI, $p > 0.05$). By the last hour of exposure T7 no bacteria were at a detectable limit in either bottle [23]. PET bottles tend to be chosen over glass bottles for the ease of access, being lightweight, and lack of breakage [24]. In comparison to PET, glass is less prone to scratching but as proven by this study yields the same results. The results concluded that SODIS efficacy in glass under tropical field conditions is comparable to PET plastic. SODIS users in these regions can choose either material of bottle depending on availability and preference of the user, but the use of PET bottles is not deemed a risk to humans [23].

(iii) Water turbidity

SODIS also depends on the turbidity, or measure of transparency due to suspended particles, of the water. Turbidity and fecal coliforms are used as water pollution indicators, as they exhibit a strong relationship with one another. SODIS is unsuitable in areas with > 30 NTU, unless the water can be pre-treated or filtered [13,17]. Preferably the drinking water after treatment should have < 1 NTU, but 5 NTU is acceptable for small or rural water facilities [18]. Studies such as Joyce et al. have explored the inactivation of fecal matter in water with > 200 NTU, concluding the water must be over 55 °C to be successful in inactivation with this level of suspended particles. Haider et al. researched how turbidity impacts the coliform count in a drinking water sample as seen below in Figure 6.

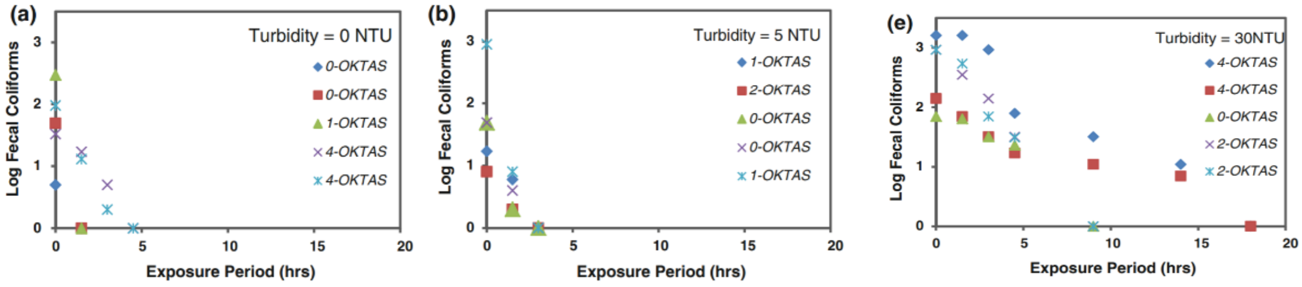

Figure 6. Fecal Coliform count at various turbidites [18].

It was found that as the NTU increases (0,5,30 NTU), a longer exposure time is needed to eliminate the fecal coliforms. Turbidites up to 5 NTU require only 2-4 hours of irradiation on a sunny day to effect inactivation, but up to 8 hours with heavy cloud coverage. For water with turbidites ranging from 5-10 NTU, 4-7 hours of exposure are required for a sunny day and 6-12 for a covered sky. Turbidites ranging from 20 to 30 NTU require 6-12 hours of exposure with sunny conditions, and 24 to 48 hours with cloudy conditions [18].

(iv) Community Acceptance/Behavioral Change

The SODIS method is a practice that can be highly effective if it continues to be utilized and paired with a promotional strategy. Successful implementation requires behavior change and alteration to daily life, to reduce health risks. This has proven to be a challenge as Eawag supported projects report that average adoption rates range from 30%-60%, with a decrease following the end of the promotional stage [13]. Eawag has identified the key to a successful campaign includes associating

SODIS use with “happiness, empowerment, financial savings, and gain of social status” [13]. Concepts such as improved water quality/health, empowerment of mothers that have the control to impact family health, social status gain, time saving, financial savings, and reduced absence from school and work due to illness need to be emphasized to gain a following from within the community[13]. In order to be successful in SODIS promotion, factors such as risks, attitudes, norms, and ability must all be taken into consideration, as they can impact the effectiveness of promotion. Below outlines the RANAS model in Figure 6, beginning with identifying the needs of the targeted audience.

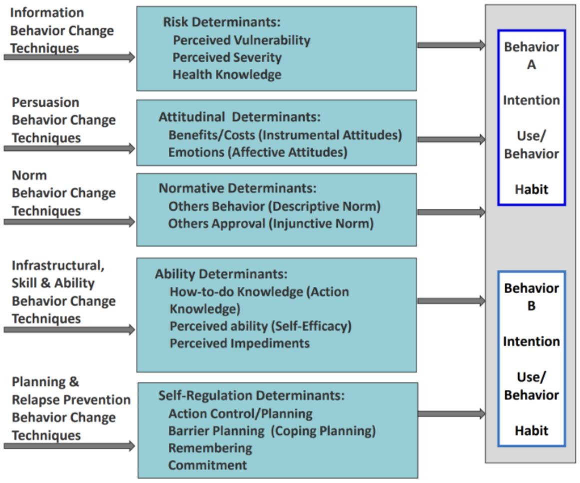

Figure 6. Implementing behavior change [13]

In the case of SODIS, initially, it is important to consider biological sex and age within the targeted audience, as a certain group in the community may handle the water within the family. Certain ages are also more susceptible to diarrheal disease and with malnourishment are at a higher risk of health detriments. Next, a behavior is targeted; in this case it is changing the behavior of drinking contaminated water, to only drinking clean SODIS treated water. Lastly, it is important to identify how this change will be implemented, or the action that is required. This model can therefore influence project planning, by adjusting the behavior change campaign to the target audience, and the critical factors that must be addressed.

Challenges in adopting an at home water treatment method may include whether the water treatment system is associated with poverty and lack of resources. A community is less likely to adopt than if it is associated with positive emotions. Approval from those with social status in the community has proven to encourage other members to participate. Local authorities, health professionals, religious leaders are all examples of personnel that the community will look to for endorsement[4].

After completing research, the following scientific studies describe successful aspects of promotional strategies:

Table 3. Sociological research on promotional strategies, adapted from [13].

Research	Findings	References
Tamas and Mosler (2009)	When participants make public commitments to continuing SODIS, and receive prompts for remembering, this had a positive impact on continued usage. The public commitments and prompts were usually given by health care volunteers, schools, and the radio.	[25]
Christen, Pacheco et al. (2011)	Correlation between SODIS participation and "frequency of promotional interactions, the gender of household members, ownership of a latrine, and the presence of malnourished children" .	[26]
Kraemer and Mosler (2010)	SODIS participation increases " if it is easier for people to remember to use SODIS, if they are convinced that untreated water is unhealthy, and if people believe that others think positively about them when they use SODIS".	[27]
Tamas & Hans-Joachim (2011) and Mosler & Kraemer (2012)	Explored "how psychological factors change from initial uptake to long term use (or relapse)", suggesting to " increase visibility in the community, include daily routine planning as part of household training and fostering remembrance of SODIS use by distributing stickers and posters".	[28,29]

Overall, there is an emphasis on promotional strategies with a favorable attitude, a higher population of malnourished children, increased knowledge of diarrheal disease causes, and increased visibility in the community. Additionally, home visits from promoters, household training, and public commitments proved to be more effective than a general event or fair for the entire community [13]. Many current SODIS programs are pilot projects, implemented on a smaller scale. This allows interpersonal communication, where the promotion tools can be specifically tailored to the target population [4]. In comparison to large campaigns, these may be supported by national health authorities that community members know and trust. Media can be endorsed by the government and educational institutions [4].

Conclusion

Globally 842,000 deaths annually are attributed to the lack of clean drinking water, poor sanitation, and hygiene [30]. In conclusion, the implementation of the SODIS program aims to promote a happier, healthier, and more modern lifestyle in addressing the basic need of clean drinking water. With increased human health, and reduction of waterborne illnesses, communities can also be positively impacted socially and economically. By treating unsafe drinking water, there will be a reduction in absences from school and work due to gastrointestinal issues. Adults will not have to fear contamination when providing water for their families, and children can properly learn in school without the burden of poor health. SODIS is also intended to promote empowerment for women, who often have responsibilities concerning their family's water supply. With clean water comes social status gain to families in low-income areas, as they can now provide clean drinking water for themselves and potential guests. Financially, SODIS is indeed able to reduce treatment costs when compared to alternatives such as chlorination, ceramic filters, and slow sand filtration. SODIS is able to tackle one of the most harmful bacteria *E. coli* at 99.99%, while virtually only costing the price of a single-use plastic water bottle. Additionally, in comparison to alternatives, SODIS has proven to effect a reduction in diarrheal disease in a range from 8-86% and requires the least amount of maintenance, differentiating it from the other alternatives explored in table 1[3].

Although SODIS serves as a safe and effective at home water treatment system to communities looking for a low cost, efficient alternative to their current methods, there are still limitations to overcome. Location is an important factor to take into consideration, as without strong UV rays, disinfection is unable to occur. Areas between 30 degrees latitude North and South thrive with SODIS as their geographical location allows for effective inactivation of microorganisms [14]. Moreover, the issue of turbidity must be addressed, where SODIS requires a pre-filter of particulate matter or the system will not be effective. A pre-filter requires an additional step that some may find not as user friendly. Another hurdle is community acceptance and preconceived notions about the SODIS process. As SODIS is implemented on a wider and larger scale, research regarding its effectiveness and best promotional strategies can improve the process for the future.

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