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Waterborne Diseases and Household Water Treatment and Safe Storage (HWTS) Techniques: A Review

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ABSTRACT

Diarrheal diseases are a major cause of death in low- and middle-income countries where houses do not have access to a safe drinking water source. Many of these diarrheal diseases are caused by waterborne diseases transferred to their host through fecally contaminated water. The implementation of household water treatment techniques such as chlorination, filtration, and UV radiation serve as temporary solutions to decontaminate drinking water for households that do not have access to a safe water source. These solutions coupled with safe storage practices – can aid in the reduction of diarrheal diseases, especially in low and middle-income countries. This paper aims to describe these temporary techniques and certain water-transmitted diseases to provide more insight into these systems.

Introduction

Each year, diarrheal diseases, originating from contaminated drinking water and improper sanitation and hygiene, lead to the deaths of over one million people.[53] Restricted access to safe drinking water is a prevalent problem in many African, Middle Eastern, and Asian countries.[47] Many countries in these regions are considered low- and middle-income countries (LMIC), meaning they need more financial and technological resources to combat unsafe drinking water. Providing individuals access to safe drinking water is essential as it improves their quality of life and reduces their risk of contracting water-borne diseases.[53]

Water-borne diseases are contracted from drinking water contaminated by pathogens such as helminths, viruses, protozoa, and bacteria. The ingestion of these pathogens from contaminated water can lead to diseases such as cholera, E. coli, rotavirus, and cryptosporidiosis.[53] These diseases, usually transmitted through fecal matter that contaminates drinking water, can lead to severe vomiting, and diarrhea. These diseases are extremely dangerous as untreated individuals experience severe and rapid dehydration which can lead to death in a matter of hours.[53]

Recognizing the health risks of these water-borne diseases, in 2012 the United Nations included an objective of achieving safe drinking water in their Sustainable Development Goals. In their goal 6.1, they aimed by 2030 to attain global and equal availability of clean and inexpensive drinking water for every person.[46] The objectives required to achieve this goal vary across countries, and the United Nations recommends that each country sets its individual goals based on its resources and limitations.[46]

Household water treatment methods serve as temporary ways for communities and households to access safe drinking water when a safe drinking water source is inaccessible.[47] The long-term goal is to establish a safe drinking water source, which is a water supply that lacks fecal and chemical contaminants, is accessible to the household when necessary, and is located on the land of the household.[53] A safe water source can vary in design and structure, and includes: home water supplies, communal water taps, drilled wells, safeguarded water springs, and rainwater harvesting.[53] Household water treatment is necessary to provide a temporary safe water source, as over 2.2 billion people lack access to a permanent safe water source.[53] Household water treatment can help address this challenge by providing relatively inexpensive and easily implemented methods to decontaminate drinking water. Additionally, with various types of household water treatment methods existing, people can select the treatment type that meets their specific financial and regional needs.

In areas of water scarcity where an individual cannot access a safe drinking water source, different water treatment options are available to reduce the number of pathogens in the drinking water. The most common household water treatment options for decontaminating water include boiling, filtration, chlorine disinfection, and ultraviolet light.[10] Although not always entirely effective and accessible, these different treatment options aid in providing a temporary solution for homes to receive cleaner drinking water.[47] These various treatment options each have their advantages and disadvantages, and some usually work better in certain areas or regions and with certain types of water. For example, Solar Water Disinfection (SODIS), a form of ultraviolet light treatment, is most effective in areas closest to the equator and with water that is not turbid.[31] Furthermore, these treatment options may be used in combination with each other to ensure that harmful pathogens are removed from the water.[43] Paired with safe storage, these treatment options can reduce an individual's risk of contracting water-borne disease.[17]

This literature review aims to convey the importance of safe drinking water by describing the potential negative health effects associated with the ingestion of water-borne pathogens. Furthermore, this paper will outline the challenges and potential preventative efforts that can be made for different pathogens, such as vaccines, while highlighting the challenges and solutions of improving human health in cases of potentially contaminated drinking water sources. Additionally, this research paper aims to describe the crucial temporary solutions used to decontaminate drinking water when a safe water source is unavailable in low-resource settings.

Methods

To describe and present the challenges of microbial contaminants and the crucial treatment options for HWTS, I conducted a literature review of reputable sources that provide context to the historical and biological effects of the common pathogens that contaminate drinking water, including the World Health Organization,[52-54] the National Library of Medicine,[3-4,18,26-30,32] and the United Nations.[46-48]

Results & Discussion

Microbiological Contaminants in Drinking Water

Waterborne diseases are diseases caused by the ingestion of water contaminated by pathogenic organisms.[34] Diarrhea is the most common symptom of waterborne disease, however, vomiting and fever may occur.[34] Some waterborne diseases, such as cholera, may be fatal as diarrhea results in rapid water loss and dehydration.[34] Waterborne diseases are responsible for the deaths of approximately 2.2 million people annually; 1.4 million of these reported deaths are children.[41] These waterborne diseases are caused by infections from pathogens such as bacteria, protozoa, viruses, and helminths that reside in the drinking water.[41] The accidental contamination of drinking water with fecal matter either from humans or animals is the most common cause of the pathogens in drinking water.[38] While these different types of pathogens differ in size, taxonomy, and health risk, each type plays a critical role in inhibiting people's access to safe drinking water.[41]

Bacteria

Bacteria are found all around us.[19] Although many types of bacteria are extremely beneficial, some are pathogenic and may lead to dangerous and fatal diseases.[3] Bacteria are single-celled organisms that are approximately 1 to 10 microns in length and 0.2 to 1 microns in width, which makes them smaller than protozoa and helminths, but larger than viruses.[50] Many different types of bacteria contribute to waterborne diseases such as Vibrio cholerae, and strains of Escherichia Coli, Salmonella, and Shigella.[3]

Cholera: Cholera, a disease caused by the bacterial species, Vibrio cholerae, infected 427,697 people across 44 countries in 2022; 2,349 of these people were killed by this disease.[52] This was a 52 percent increase in cases from 2021 where 223,370 cases were reported across 35 countries.[22] This surge in cholera cases is largely attributed to improper water distribution, an increase in poverty, and a rise in conflicts that restrict an individual's access to safe drinking water.[48] These reported cases vary greatly, but scientists estimate there are 3 to 5 million cases of Cholera, including 100,000 deaths from Cholera, each year.[52]

It is believed that the variations in the data are caused by a country's reluctance to report Cholera outbreaks as it could affect their tourism or trading abilities.[52] Additionally, many people infected with Cholera exhibit mild to no symptoms, which could lead to a lower amount of diagnosed Cholera cases.[52] In recent history, LMICs in Africa, southern Asia and Latin America have experienced the greatest burden of cholera cases due to the limited sanitation, and limited financial and medical opportunities, countries in these regions have to deal with the demand placed on these already burdened systems by Cholera outbreaks.[25] Children under the age of five are most susceptible to Cholera in locations where an epidemic is prevalent.[25] This is mainly due to the higher risk of exposure to the pathogen due to its prevalence in the community and the surrounding pressure placed on an already limited resource for water, sanitation and hygiene.

Since Cholera first emerged as a widely recognized disease in the 19th century, there have been seven dangerous worldwide cholera pandemics that have started in Asia and spread through Europe and Africa until they eventually reached South America.[3] The first worldwide pandemic began in 1817 and ended in 1826. The seventh Cholera pandemic began in 1961.[3] Still today, cholera is considered an epidemic in approximately 50 countries, mainly located in Southern and Southeast Asia.[40]

In 1885, the first cholera vaccine was created.[30] Today, the World Health Organization recognizes three oral cholera vaccines, all needing two doses to work effectively and provide complete protection.[52] Over 145 million doses of these vaccines have been distributed during extensive vaccination movements.[52] However, ultimately the implementation of safe water, sanitation, and hygiene (WASH) strategies along with the vaccine will help to end this growing Cholera epidemic.[52]

Due to the evident demand for a solution to this ongoing crisis, the Global Task Force on Cholera Control (GTFCC) implemented a strategy called Ending Cholera: A Global Roadmap to 2030 that plans to decrease deaths caused by Cholera by 90 percent and eradicate the disease in at least 20 LMIC countries by 2030.[52] The GTFCC created a three-pronged approach to reach its goal.[52] In one of the three strategies, the GTFCC called for countries and their governments to focus on areas that experience a high amount of Cholera cases, and to implement WASH procedures along with Cholera vaccines to stop the transmission of Cholera in these areas.[52] In May 2018, the World Health Assembly approved the plan.[52]

Vibrio cholerae is an anaerobic bacterium that grows best at 40 degrees Celsius.[3] Sodium chloride plays a vital role in activating this growth.[3] Therefore, Vibrio cholerae is most commonly found in warm water ecosystems where they latch to plants, insects, crustaceans, threadlike green algae, and zooplankton.[44] Vibrio cholerae contains 200 serotypes which makes it an extremely diverse bacteria.[3] Serotypes are classifications of different types of bacteria and viruses within a certain species based on specific surface characteristics and structure.[9] However, there are only two serovarieties that form Cholera disease: O1 and O139.[3] Serotype O139 was first discovered in Bangladesh in 1992 and has only been observed in Asia, whereas serotype O1 is found globally and is responsible for the majority of global cholera cases.[52] The symptoms of Cholera these two serotypes produce are indistinguishable from each other.[52]

A person can be exposed to Vibrio cholerae if they drink water or eat foods contaminated by the feces of a person who had Cholera.[52] In fact, Vibrio cholerae is found in the feces of a contaminated person 1-10 days after their initial infection.[52] Typically, a person must consume a high dosage of Vibrio cholerae to contract Cholera, usually between 10^6 to 10^{11} colony-forming units (CFU).[42] This is because Vibrio cholerae, once consumed, infiltrates the small intestine, which is an extremely acidic environment in which the base-thriving Vibrio cholerae needs higher numbers to survive.[42] In the small intestine, this species colonizes and produces cholera toxin which produces the symptoms of Cholera disease.[42]

It takes about 12 hours to 5 days for a person to exhibit symptoms after ingesting Vibrio cholerae (WHO).[52] The most common symptom is severe, watery diarrhea that may be more than 1 liter per hour.[3] This can cause dehydration, muscular pains, low potassium levels in the blood, and circulatory collapse may occur.[3] Death can occur within a few hours after the onset of symptoms due to the large water loss from diarrhea.[3] If a person does not receive treatment to combat their loss of water, salts, and potassium, they have a 50 percent mortality rate.[3] In the case of light or less severe dehydration, an oral rehydration solution (ORS), composed of a mixture of sugar, water, and salts, can be administered.[3] However, in severe cases, intravenous administration is vital to prevent death.[3]

Escherichia coli: Escherichia coli, commonly called E. coli, are bacteria located within the intestines and feces of homiotherms.[51] E. coli is extremely diverse, with over 700 serotypes.[35] Although many of these serotypes are harmless and even beneficial to the body, protecting the gut from pathogens and creating vitamin K2, some serotypes can be extremely harmful.[37] E. coli are anaerobic bacteria with a length of 2 micrometers and a diameter of 0.5 micrometers.[37] The most advantageous growth temperature for E. coli is 37 degrees Celsius.[37] There are six commonly recognized strains of E. coli that cause diarrhea.[49] However, Enterotoxigenic E. coli (ETEC) is the primary strain in low-income settings, and it is transmitted through contaminated water.[49]

Infection due to ETEC is caused by the ingestion of water or food contaminated with animal feces or feces of a person who has ETEC.[49] The symptoms of ETEC include watery diarrhea without mucus, pus, or blood, as well as vomiting and fever.[49] The groups most at risk for contracting ETEC are young children under two years old in warm or tropical climates and travelers going to warm or tropical climates.[28] Travelers are also extremely susceptible to contracting ETEC as their immune systems are not developed and accustomed to fighting the pathogen.[28]

E. coli are a type of coliform bacteria, which are organisms that reside in the intestines of humans and warm-blooded animals.[51] A subcategory of coliform bacteria is fecal coliform bacteria, which reside in the intestines of humans and other warm-blooded animals.[51] Since fecal coliform bacteria can be separated from the whole of coliform bacteria at high temperatures (44.5 degrees Celsius), they are used to indicate fecal contamination in water, as other pathogenic organisms thrive in the same environments.[51]

E. coli is most known for its use as a fecal indicator bacteria to help measure water quality.[37] It is considered to be the best and most effective indicator of fecal matter compared to other fecal coliforms.[37] This is because testing E. coli in drinking water is inexpensive, quick, sensitive, and specific. Additionally, E. coli is used as the preferred fecal indicator because of its prevalence in human and animal feces, and its inability to survive outside of the intestinal tract except in tropical environments; this helps water testers to know if fecal contamination happened recently.[37] Unlike previously used fecal coliforms, E. coli rarely exists in the environment on its own due to its fecal origin, which helps ensure water quality testers that the presence of E. coli is due to fecal contamination and additional factors.[37]

Although E. coli is preferred by microbiological water testers, it can cause problems with using E. coli as a fecal contamination indicator.[37] One issue is that compared to the other types of fecal bacteria, E. coli is seen in smaller amounts, which makes it more difficult to detect.[37] Furthermore, E. coli can be found in tropical environments outside of fecal matter, which means that testing in these areas may give misleading results since the E. coli may not be fecal in origin.[37] In summary, E. coli does not completely determine the occurrence of fecal contamination in culture tests for microbiological water quality testing.[37]

This concept is true for all culture tests, as results underestimate the amount of E. coli in a given sample.[37] One primary reason for this is that the media in which healthy coliforms are placed is not ideal for their growth.[37] Another reason is that the coliforms in the environment are usually not in their optimal growth conditions which makes the regeneration of these coliforms on growth media very difficult.[37] Although these factors may lead to misleading conclusions about the presence or absence of fecal coliforms in a sample, it does help give an idea of the presence of fecal-borne pathogens.[37] Additionally, E. coli testing may not always yield the correct number of pathogens in a sample, but it helps to indicate the risk level of fecal-borne pathogens in a given sample.[37]

Viruses

Viruses are pieces of genetic material, either DNA or RNA, located within defensive shells called capsids.[20] Viruses are extremely tiny, between 20 to 400 nanometers, which makes them smaller than bacteria, helminths, and protozoa.[20] When viruses infect their host, they reproduce by seizing the cells of their host to make more viruses.[20] Waterborne viruses include Rotavirus and Hepatitis A and E.[26]

Rotavirus: Rotavirus is a pathogenic virus that is the primary cause of acute diarrhea cases in children worldwide.[21] There are ten known categories of Rotavirus, labeled with the letters A-J, with Rotavirus A being responsible for the majority of child Rotavirus cases.[29]

Rotavirus is mainly spread through the fecal-oral route, either from consuming water or food containing feces or having feces on the hand which then is brought to the mouth.[24] Additionally, Rotavirus can be transmitted by contact between two people.[24] Rotavirus is a highly contagious virus, and Rotavirus symptoms occur approximately two days after infection and symptoms can last between three to eight days.[24] Rotavirus symptoms include fever, vomiting, malaise, and diarrhea.[21] Rotavirus is released in vomit and diarrhea in high amounts and thus can re-contaminate drinking water if WASH is not practiced.[21] Rotavirus symptoms include fever, vomiting, malaise, and diarrhea, through which Rotavirus is released in high amounts and can re-contaminate drinking water if WASH is not practiced.[21] Oral rehydration solutions (ORS) can be used to treat dehydration caused by rapid water loss from diarrhea and vomiting.[21] However, vomiting can make the ORS less effective, and in severe cases, intravenous treatment may be necessary to combat dehydration.[21]

Prior to the creation of Rotavirus vaccines, Rotavirus was notorious for causing more than 500,000 deaths in children under the age of five each year.[21] The implementation of four oral rotavirus vaccines has reduced the death rate to roughly 200,000 deaths in children under the age of five each year.[21] Of these 200,000 fatal Rotavirus cases, more than 90 percent were located in low-income countries.[21] This is due to factors such as malnutrition and lack of availability to healthcare such as vaccines and ORS.[21] Although vaccination is the key to ending the widespread transmission of Rotavirus, WASH practices aid as a supplemental solution to help stop the spread of Rotavirus, especially in areas where access to healthcare and vaccination is limited.[24]

Protozoa

Protozoa are unicellular organisms.[33] They are primarily found in moist environments such as in aquatic ecosystems and the soil.[33] Protozoa vary greatly in size from 1 micrometer to 2,000 micrometers, which makes them larger than bacteria and viruses but smaller than Helminths.[39] There are parasitic protozoa that inhabit plants, animals, and humans where they cause disease.[33] Many waterborne diseases are caused by parasitic protozoa including cryptosporidium and giardia.[32]

Cryptosporidium: In humans, Cryptosporidiosis, a disease credited with being the leading cause of death in children between the ages of 12 to 23 months, is caused by two types of protozoa: Cryptosporidium hominis and Cryptosporidium parvum.[2] One way that a person ingests these pathogenic protozoa is when they consume fecally contaminated food or water.[2] These protozoa usually affect the small intestine, which results in symptoms such as diarrhea, fluid loss, weight reduction, stomach pain, fever, and vomiting that can remain for up to two weeks.[28]

An infected person’s feces contain pathogenic Cryptosporidium hominis and Cryptosporidium parvum, which can be spread to others through improper sewage and sanitation practices.[7] As a result, drinking water sources can become contaminated, which can lead to a rapid spread of this disease.[7] For these reasons, practicing WASH techniques is essential for ending the transmission of these pathogenic protozoa.[2] Young children are extremely susceptible to Cryptosporidiosis, especially in LMIC.[2] In Sub-Saharan Africa and South Asia, Cryptosporidiosis is the second most common cause of acute diarrhea in children under five years old.[2]

Helminths

Helminths are parasitic worms that can be transmitted to humans and other animals through ingestion.[4] If the feces of a person infected with a parasitic worm contaminates a household's drinking water, other people who drink the water can become infected with parasitic worms as the eggs of the worm are spread through the infected person's feces.[4] Once ingested, these eggs can hatch in the stomach where they can wreak havoc on their host. This infection is called helminthiasis or a worm infection.[4] Three main categories of Helminths affect humans: flukes, tapeworms, and roundworms.[4] Helminths can vary greatly in size from less than one millimeter to greater than a meter.[4] Regardless, they are larger than viruses, protozoa, and bacteria.[4] Due to their size, Helminths are easily removed from contaminated drinking water through the household water treatment process of filtration.[43] Because of their ability to be removed through filtration techniques, Helminths will not be discussed further in this review.

Household Water Treatment and Safe Storage (HWTS)

Household water treatment and safe storage (HWTS) plays an integral role in reducing pathogens in drinking water.[43] HWTS is a temporary solution for households to have access to safe drinking water until piping or a safe source of drinking water can be implemented in the home.[43] There are various household water treatment options, and some are more favorable in certain water conditions or locations across the globe.[43] This review aims to cover and analyze common methods used in global household water treatment: boiling, filtration, solar disinfection, and chlorination. These household water treatment systems, along with safe storage, ensure that recontamination does not occur. This is essential in reducing the risk of diarrheal diseases in emergency scenarios or in households that do not have access to safe drinking water.[43] Additionally, in certain scenarios, these methods are most effective when they are used together in a series of steps to ensure that all microbiological pathogens are eliminated.[43]

Boiling

Boiling is an extremely effective water treatment process that has been used for centuries and is the most commonly used household water treatment system.[18] Boiling is considered to be extremely effective in killing all bacteria, viruses, and protozoa as it uses heat to damage these pathogen's integral structures and life processes, thus rendering the pathogens ineffective in causing disease.[13] Boiling is considered to be a form of pasteurization, as it kills harmful microbiological organisms.[36]

To be successful, boiling must reach a specific temperature to target these pathogenic organisms as well as be held at a specific time at these temperatures.[13] There are some differences between the recommended time to boil water. For example, the American Centers for Disease Control and Prevention (CDC) recommends that households located at altitudes of under 6,500 feet should bring their water to a roiling boil for one minute, while for households located at an altitude over 6,500 feet, water should be boiled for three minutes.[5] In comparison, The Centre for Affordable Water and Sanitation Technology (CAWST) advises that water should be boiled for one minute with an additional minute added by an altitude increase of 3,280 feet.[13] Despite these discrepancies, boiling is extremely effective in killing microbiological pathogens.[13]

There are many reasons for the popularity of boiling as a drinking water disinfectant. One is the widespread acceptance of boiling water as a treatment for contaminated drinking water, especially in countries where boiling is already widely used in the making of tea.[11] Additionally, boiling is relatively popular as it requires few materials, many of which are already found near or in the household such as wood and a pot for boiling water.[11]

Despite the many benefits of the implementation of boiling as a treatment for contaminated drinking water, there are some drawbacks. One issue with boiling is the flat taste that occurs as a result of the removal of dissolved oxygen from the water during boiling.[11] Although this issue can often be fixed by shaking or stirring the cooled water, it can deter people from using this water treatment option.[13] Also, highly turbid contaminated water must be filtered or drained through a cloth before it can be boiled.[13] Additionally, the use of wood to create a fire to boil water can lead to environmental issues such as deforestation.[11] If these fires are lit inside households without access to proper ventilation, the smoke accumulation inside the home can also lead to respiratory issues.[11] Furthermore, the cost of boiling is rather high compared to other household water treatment systems at $0.88 US dollars per month for households using petroleum gas and $0.69 US dollars per month for households using wood.[18]

Although boiling is extremely effective against bacteria, viruses, and protozoa, it is extremely prone to recontamination from these pathogens.[13] If decontaminated drinking water is transferred to another container, the chances of recontamination are extremely high, especially if the container has not been properly cleaned.[13] To prevent the risk of recontamination, decontaminated water should be kept in the pot that it was boiled in and then sealed with a lid.[13] The water should never be retrieved by hand or contaminated ladles as this also contributes to recontamination.[13]

Boiling as a form of household water treatment is best suited for areas that have access to fuel, such as a highly forested location.[11] Additionally, these areas would likely be located in a culture where boiling water is widely accepted, the water is relatively clear, and water can be stored safely after boiling.[11] Table 1 displays the cost, effectiveness, advantages, and disadvantages of boiling in comparison to other forms of household water treatment.

Solar Disinfection (SODIS)

A relatively new technology for household water treatment called Solar Disinfection (SODIS) uses ultraviolet radiation to treat contaminated water.[16] In SODIS, contaminated water is placed in plastic bottles constructed from polyethylene terephthalate (PET).[16] PET bottles are the preferred container for SODIS due to their smaller size, which allows them to effectively remove pathogenic microorganisms.[31] Furthermore, PET bottles are widely accepted due to their lack of Bisphenol A (BPA) a carcinogenic substance found in some plastic bottles that can potentially leak into the drinking water.[31] These bottles are then placed in direct sunlight, usually on the household's roof.[31] SODIS mainly uses two types of ultraviolet rays to deactivate pathogenic microorganisms in the water: UV-B and UV-A.[31] Although UV-B inactivates a pathogen's effectiveness by deteriorating its DNA or RNA, it only plays a minor role in SODIS as the PET bottles absorb most UV-B radiation before it can reach the pathogens.[31] While UV-A does not directly damage pathogens, it has a more significant role in SODIS as it creates reactive oxygen species.[31] These species then react with these micro-organisms, damaging their DNA and proteins in the process.[31] The sun's heat can also deteriorate the pathogen's structure through pasteurization, and its effects on the pathogenic organisms are determined by the irradiation intensity, ambient temperature, and location of the PET bottle.[31] If the PET bottles are located in an area where the temperature is above 45 degrees to 50 degrees Celsius, this pasteurization can couple with the ultraviolet rays to target and destroy these microbiological pathogens at a faster and more effective rate.[31] For these reasons, bacteria are particularly susceptible to the effects of SODIS as their structural proteins and enzymes are damaged by the effects of UV-A radiation, which leads to cell deactivation and death.[31] The process of SODIS is less effective against viruses, and even less effective against protozoa.[31] Although these reasons are not entirely understood by scientists, for protozoa, it is thought that cysts or spore-forming protozoa are less resistant to environmental stressors such as UV radiation.[31] As a result, SODIS is not entirely efficient in the removal of protozoa, and a higher irradiation quantity may be needed to completely remove these pathogens.[31]

For SODIS to be the most effective, it is recommended by the CAWST that the PET bottles be placed horizontally to ensure maximum sunlight exposure. The bottles should be placed directly in the sun for six hours.[16] SODIS should never be applied during days of continual rainfall.[16] The PET bottles should constantly be in the sun as the effectiveness of SODIS is directly dependent on the amount of sunlight the PET bottles receive.[16] For this reason, SODIS is most effective in areas between latitudes 15°N and 35°N as well as 15°S and 35°S.[16] In areas where sunlight is low, PET bottles can be placed on sunlight-reflecting areas such as zinc roofs, which helps the water temperature increase by 5 degrees Celsius.[16] After the water has been decontaminated through SODIS, the water should be used directly from the PET bottle to reduce the risk of recontamination.[16] In this way, the PET bottle is used as a safe storage container.[16]

SODIS's effectiveness against bacteria is extremely beneficial.[16] Additionally, the ability of the PET bottle to be used as a safe storage container prevents the need to transfer the decontaminated water, which reduces the risk of recontamination.[16] Furthermore, the only materials needed for use are PET bottles, which only have to be replaced periodically if they become scratched or damaged.[16] This makes SODIS extremely cheap. SODIS requires an estimated yearly cost of $0.63 US dollars.[27] SODIS is also only dependent on the supply of PET bottles, which makes it less dependent on supply chains than other HWTS methods.[31] Additionally, SODIS's dependability on sunlight means that it doesn't require additional energy sources, and it is extremely easy to implement on a household level.[31] Finally, the decontamination process of SODIS does not change the taste of the water, which is beneficial for the consumer.[31]

Despite the many benefits of SODIS, there are some drawbacks, such as its limited removal of certain viruses and protozoa.[16] Additionally, SODIS's dependence on PET bottle availability and sunlight can make its use difficult in certain locations.[16] Furthermore, the length of disinfection and the higher amount of labor that SODIS requires can deter users from this method.[31] SODIS is also not effective against highly turbid waters because the particles in the water can deflect the UV radiation from the sun.[31] Finally, in certain regions, SODIS is viewed as a HWTS method that only people with low income, use which can deter people from implementing this water treatment technique.[31]

SODIS is best suited for areas that receive high amounts of intense and daily sunlight.[16] Furhermore, due to its low cost, SODIS is extremely beneficial in low-income areas that do not have access to certain supply chains or energy sources.[31] SODIS should not be used with turbid water as it will render the treatment ineffective.[27] Table 1 displays the cost, effectiveness, advantages, and disadvantages of SODIS in comparison to other forms of household water treatment.

Chlorine

Chlorination is a technology that is used to decontaminate drinking water using chemicals.[15] Chlorine for drinking water purification can be sold in liquid or tablet form from various brands.[15] Additionally, chlorine packages can be sold in different sizes with a chlorine concentration range of 0.5 percent to 10 percent.[15] If a household is unable to access Chlorine tabs or packets, liquid household bleach can be used in low doses as a substitute.[15] These packages will typically provide instructions on how to add chlorine to the contaminated water.[15] If the contaminated water is highly turbid, it should be filtered before treatment to remove floating objects and to enhance the reaction between chlorine and the pathogens in the water.[15] Additionally, the contaminated water should have a pH range of 5.5 to 7.5. If the water has a pH level above 9, treatment will be ineffective.[15]

During chlorine treatment, when chlorine is added to water, it creates hydrochloric acid.[15] Through oxidation, chlorine reacts with pathogenic microorganisms to kill them.[15] When chlorine is mixed with water, there can be three outcomes: consumed chlorine, combined chlorine, and free chlorine residual (FRC).[15] For consumed chlorine to occur, in the process of oxidation, some chlorine reacts with organic matter and pathogenic microorganisms, killing them.[15] Combined chlorine is a new chlorine compound that is formed when some chlorine reacts with organic matter, ammonia, and iron.[15] FRC is formed from leftover chlorine that is not consumed or combined.[15] The FRC plays an important role in ensuring that treated water is not recontaminated.[15] Additionally, the FRC is the most successful type of chlorine for disinfection, especially for viruses.[15]

Chlorine's extreme effectiveness against bacteria makes it beneficial to users. Additionally, chlorine is relatively effective against most forms of viruses.[15] Chlorine is also extremely cheap, with a cost of $0.66 US dollars per year, although this can depend on location.[27] Chlorine is also relatively easy to use, which makes it widely accepted by its users.[12] Finally, the FRC means that water treated with chlorine has a low risk of recontamination.[15]

There are some potential drawbacks to using chlorine as a water treatment option. One of these issues is that chlorine has little to no effectiveness against protozoa such as cryptosporidium.[15] Additionally, residual chlorine in the water leads to a change in the taste and odor of the drinking water, which can deter consumers from its use.[15] Furthermore, when chlorine interacts with the organic material in the contaminated water, it can create additional products such as trihalomethanes (THMs), which can potentially be carcinogenic.[15] Additionally, chlorine is not suitable for highly turbid water, and its need for chlorine packets or bottles to operate means that it is not suitable for remote areas.[15]

Chlorine is best suited for areas that have low turbidity in their water, with pH levels between 5.5 to 7.5.[15] Additionally, chlorine use is best in urban areas or areas because they can access a supply chain for chlorine packets easily.[12] Table 1 displays the cost, effectiveness, advantages, and disadvantages of chlorination in comparison to other forms of household water treatment.

Ceramic Filtration

Ceramic filtration is a drinking water treatment process that has been used for centuries.[14] Although there are many types of ceramic filters in use globally, the most widely administered is the Potters for Peace (PFP) filter.[8] This style of filter has a design structure that is similar to a flowerpot.[8] The PFP filter is infused with colloidal silver, which is an antibacterial material that helps to deactivate bacteria in contaminated water as well as prevent the growth of bacteria in the ceramic filter.[14] The colloidal silver helps to ensure that 100 percent of the bacteria is removed during the filtration process.[45] The PFP filter can hold up to 8.2 liters of water, and it is located in a 20 to 30-liter plastic or ceramic container with a spigot.[1] The creation of an additional container for the PFP model helps to create safe storage, which prevents recontamination.[14] A lid sits above the entire structure to prevent further contamination.[14]

The small pore size of the PFP ceramic filter, between 0.6 to 3 micrometers, helps to effectively remove bacteria and protozoa from the contaminated water.[1] However, due to viruses' extremely small size, 20 to 400 nanometers, many can pass through the filter.[20] Thus, ceramic filters are effective in reducing pathogenic bacteria and protozoa, but are less effective in the reduction of pathogenic viruses.[14]

As contaminated water is poured into the ceramic filter, the water is forced through the small pores at the bottom of the filter.[14] These pores effectively remove the pathogenic bacteria and protozoa in the water.[14] The water is then kept in the container below the ceramic filter, and when the household needs water the spigot can be opened.[14] This method keeps the water from being recontaminated by dirty hands or an improperly cleaned storage vessel.[14] If the contaminated water is highly turbid, as defined by a turbidity level more than 50 Nephelometric Turbidity units (NTU), then the water should be drained through a cloth to prevent buildup in the pores of the ceramic filter.[14] Additionally, the ceramic filter should be lightly cleaned regularly to prevent accumulation or buildup that can block the pores.[14] It is recommended by CAWST that the ceramic filter should be replaced every one to two years, and that the filter should be replaced immediately if visible cracks begin to appear.[14] Likewise, the flow rate will become slower over time, even with regular cleanings, as more particles will accumulate to block the pores of the filter.[14]

There are many benefits of using ceramic filtration to treat contaminated water. One benefit is the filter's effective removal of protozoa and bacteria.[8] Additionally, the filter is widely accepted due to its easy application after proper education of operation.[8] Ceramic filters usually have a low one-time cost — however, the price of the filter can quickly rise due to breakages.[8] Another benefit of ceramic filters is that the filter can be used for an extended period, up to five years, if no breakage occurs.[14]

Although ceramic filters are effective against protozoa and bacteria, they have limited effectiveness against viruses.[14] Additionally, if the ceramic filter is not drained into a safe storage container, there is an additional risk of recontamination.[14] The ceramic filters also have a low flow rate of 1 to 2 liters per hour, which decreases over time as particles accumulate in the pores of the filter.[14] Additionally, as many ceramic filters are manufactured globally the quality of some filters may vary, which means that some manufactured ceramic filters are prone to breakage.[27] This can lead to a relatively high price for ceramic filters of $3.03 US dollars per year.[27] This low flow rate, along with the easy breakage of some ceramic filters, can deter consumers from using this type of household water treatment. The need to clean the ceramic filter regularly can also deter consumers. Finally, basic education on the operation of the filter is necessary to ensure that it is kept clean.[14] If the ceramic filter is not cleaned properly, it can get recontaminated or lead to unsuccessful water decontamination attempts.[14]

Ceramic filters are best suited for areas that are near a supply chain for ceramic filters or a ceramic filter manufacturer.[8] Additionally, households need to be in an area where they can receive replacement parts from a distribution network.[8] Finally, households should have the ability to receive instructions and training on how to correctly use and maintain the ceramic filter.[8] Table 1 displays the cost, effectiveness, advantages, and disadvantages of ceramic filters in comparison to other forms of household water treatment.

Table 1. Comparison of the Different Methods of HWTS

Treatment Type	Cost (per person)	Normalized Cost	Efficacy: in Bacteria	Efficacy: in Protozoa	Efficacy: in Viruses	Advantages	Disadvantages
Boiling	0-$10.56 per year[27] Petroleum Gas: $0.88 per month[18] Wood: $0.69 per month[18]	0-$10.56 per year Petroleum Gas: $10.56 per year Wood: $8.28 per year	High	High	High	-Cultural Acceptance -Few Materials Needed	-Flat Taste -Ineffective in turbid water -Air quality -environmental issues -high cost -potential respiratory issues -prone to recontamination
SODIS	$0.63 per year[27]	$0.63 per year	High	Medium	High-Medium	-low chance for recontamination -low cost -low dependability on supply chains -no change in taste - no energy sources needed, environmentally friendly	-location dependent -unacceptable in some cultures –some dependence on supply chains -ineffective in highly turbid water -high treatment time
Ceramic	$3.03 per year[27]	$3.03 per year	High	High	Low	-easy application -cultural acceptance -lasts for an extended period (>5 years) (if no breakages) -low one-time cost (if no breakages)	–risk of recontamination (dependent on the model used) -low flow rate -breakage is common (dependent on the model used) -Filter must be cleaned regularly

Chlorine	\$0.66 per year[27]	\$0.66 per year	High	Medium-Low	Medium	-low cost (dependent on location) -easy to use -low risk of recontamination (FRC)	-change in taste and odor of water -dependent on the supply chain -by-product of THMs (potentially carcinogenic) -ineffective in highly turbid water

Safe Storage

The implementation of safe storage techniques after treating contaminated water is extremely important.[43] A study conducted with a group of Malwai refugees, who faced consistent outbreaks of cholera and diarrheal diseases, found that the implementation of safe storage drastically reduced the spread of waterborne diseases.[43] The conductors of the study analyzed the source wells and found that the water had little or no microbiological pathogens. However, the water was quickly contaminated by household members retrieving the water with their hands.[43] After a study was conducted in which ¼ of the population was given a bucket that conformed to safe storage principles, it found that the tested population had a reduction of 69 percent in fecal coliform levels in household drinking water and a 31 percent reduction in diarrheal disease in children under five.[43]

After contaminated water has been treated using household water treatment techniques, it is extremely important to store the treated water safely to prevent recontamination.[23] If a household does not implement safe storage, the treated water can become even more contaminated than the source water, and the household would be susceptible to contracting diarrheal diseases.[23] There are various types of safe storage containers in use globally, and the size, design, and structure of the safe storage container may vary depending on the household's needs.[43] However, some design elements are essential to ensuring that treated water is not recontaminated in storage.[43] A safe storage container should have a secure lid or cover to ensure that pathogens do not enter the water.[43] Additionally, the safe storage container should have a tap, spigot, or a narrow opening so that households can retrieve treated water, but will not contaminate the water with dirty hands or ladles.[43] The container should be easy to clean, strong, and durable, and should have handles for ease of carrying and storage.[43] Additionally, the container should be affordable and manufactured locally to avoid dependence on supply chains that may not be accessible to certain regions.[43] Some examples of this include jerry cans, buckets, pots, and urns.[43] Finally, the container should be compliant with household treatment techniques, which means that multiple safe storage containers may be necessary to comply completely with the water treatment technique.[43] If chlorine or another chemical disinfectant is used the safe storage container should not consist of excessive oxidatants or other materials that could potentially result in the production of dangerous by-products in the drinking water.[43]

Many regions in LMIC use containers that conform to cultural standards, so it can be challenging to create safe storage containers that abide by these standards while also preventing the treated drinking water from recontamination.[43] In many LMIC countries, households use storage vessels that they have used since ancient times such as traditional pots contracted from natural sources such as wood or containers made from animal skin.[43] These containers may vary greatly in size and material.[43] Additionally, many developing countries, use storage containers constructed out of aluminum, steel, iron, and plastics such as jerry cans, picnic coolers, and buckets.[43]

Combination of HWTS Systems

There are many forms of household water treatment systems that a household can choose from to implement in their own home or community. The ideal household water treatment system for a given area should be specific to the needs of the household and should be easy to implement in that area.[43] When choosing the best HWTS source for a certain household, financial and regional criteria must be assessed.[43] For example, if a household does not have easy access to a supply chain then chlorination which requires a ready distribution system of chlorination tablets is not the best option for this household.[15] Sometimes, a combination of household water techniques is the best option for the complete and effective removal of pathogens from the drinking water (eawag, 2008).[43] For example, different methods can be used together to completely remove all types of pathogens from the water.[43] In one scenario, ceramic filtration and chlorination could be used together. Ceramic filtration would be used first as the ceramic filtration would remove protozoa and bacteria from the contaminated water, then through adding chlorine to the water pathogenic viruses would be effectively removed and the water would have a chlorine residual, making the water less susceptible to recontamination.[12]

Conclusion

This review discusses a variety of waterborne diseases that affect millions of people in LMIC as well as the HWTS systems in place to restrict the scale of these diseases. HWTS helps serve as a temporary solution for the long-term goal of accessibility to a safe drinking water source. Although there are many HWTS solutions available, there have been limited studies available to determine the effectiveness of certain methods as well as their consistent use in certain areas. In addition to HWTS, consistency, and safe storage practices are essential to prevent the spread of microbiological pathogens. To achieve the Sustainable Development Goals of 2030 governments must work together with scientists to study and promote the implementation of HWTS methods. Additionally, along with education and instructional classes, HWTS systems may be more beneficial to their users.

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