Assessing the efficacy of low-cost water purification methods by comparing contaminant levels with an emphasis on sustainable biodynamic cleaning

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Abstract:
Not having access to potable water is detrimental to the everyday lives of hundreds of millions of people in developing countries, forcing them to spend vital resources on securing access to one of the most basic human necessities. Purifying water, ideally with low-cost methods, is a step toward a solution. Assessing these methods is a necessary step for implementation. Water samples from a natural pond, hydrologically similar to drinking water sources in developing countries, were collected. Various inexpensive purification methods were tested, categorized by the form of energy used in purification, such as mechanical, utilizing mussel and oyster filter feeding to remove bacteria and other contaminants; gravitational, filtration through coffee filters; thermal (boiling) and others. Bacterial and pH test strips, and a turbidity meter were used to measure contaminant levels. Results indicated that the use of commercial water purification tablets (Aquatabs®) purified the pond water to potable levels, whereas boiling, or contacting with mussels or oysters, each significantly reduced contaminants when used in conjunction with eight coffee filters to strain out physical particulates. Therefore, people in developing countries, located near oyster reefs or mussel beds, may be able to utilize the mussels and oysters not only as a food source, but as sustainable, biodynamic, low-cost, and effective water purifiers. This project also disproved the efficacy of several possible purification methods, such as the application of ultraviolet light. The results from this study identified the purification methods that may be viable for use in developing countries with poor access to potable water.

Keywords:
Water quality, Potable, Filtration, Bivalves, Biodynamic, Inexpensive, Sustainable, Water purification

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Introduction:

Access to potable water is key for survival (1,2). Drinking water contaminated with dangerous chemicals and/or heavy metals can lead to skin discoloration, nervous system damage, organ damage, cancer, and more (1). Contamination with a variety of disease-causing bacteria or viruses, including typhoid and cholera, can result in stomach pain, vomiting, diarrhea, headaches, fever, kidney failure, hepatitis, and death (1). Water purification systems can help remove salt; bacterial, chemical, and physical contaminants; and neutralize extreme pH levels. However, the vast majority of purification systems available today are either too costly or are not effective across all of the aforementioned contaminants, hence developing a cheap and effective water purification system presents a daunting task.

The EPA (Environmental Protection Agency) guideline states that in order for water to be safe to drink, it must contain less than a defined concentration of various disinfectants, disinfectant byproducts, inorganic chemicals, microorganisms, organic chemicals, radionuclide contaminants, and particulate matter (3). The EPA also has a second set of recommended standards to make the water more palatable (3). Currently, over 3/4 of a billion people worldwide do not have access to clean drinking water (4). While countries have many differing standards, the worldwide standard is that drinking water should not pose a major health risk if consumed over a lifetime, a standard which has not been met globally (5).

The contaminants listed above can affect bacterial growth. Generally, bacteria grow best in neutral or slightly acidic environments (8). Chlorine has an inhibitory effect on bacterial growth (9). Nitrates have no effect on bacterial growth, while nitrites may have a small inhibitory effect (10, 11, 12, 13). Iron, lead, copper, and other metals have a slight inhibitory effect (14). Increased water hardness may promote the growth of bacteria (15). However, considering the low level of precision used for measuring bacterial growth in this experiment (as it if effectively an order-of-magnitude measurement) these effects are negligible for common bacterial species.

The current most frequently-used method to remove contaminants from water in communities without large-scale water cleaning infrastructure is boiling (16,17). Boiling is currently the surest method of treating water to make it safe for drinking (18). Notably, however, boiling does not remove all contaminants (19). This indicates that most other methods remove even fewer contaminants than boiling.

Moreover, in many poor communities, fuel for fire for boiling water can be significantly expensive, and smoke inhalation from indoor cooking fires in low-income countries (including the type of fires often used for boiling water) are estimated to cause one million deaths every year (16,17,20). In addition, gathering natural biomass fuel can take enough time in poor communities, which in turn prevents children from attending school and parents from engaging in other income earning opportunities to provide basic necessities (16,17). Other methods of purification could potentially be less dangerous and costly in person-hours, yet still be effective enough to make water potable.

The second most effective way to purify water is by using chemical disinfectants in conjunction with physical filtration devices (18). According to the Center for Disease Control (CDC), chemical disinfectants “are not as effective in controlling more resistant organisms”, and filtration does not control many microbial organisms, making this a less viable option for purifying water (18).

Another method of water purification is reverse osmosis, which is particularly appealing as it is capable of desalinating water, enabling the use of new water sources that would otherwise not be usable (21). Reverse osmosis is a method of purifying water that moves water through membranes that allow water molecules through, but restricts the passage of salt and contaminants (21). Per gallon, reverse osmosis is expected to cost \$3.00 to \$4.60 per thousand gallons, in addition to a \$29 million- to \$34 million-dollar cost of initial construction for a reverse osmosis plant (22). Thus, reverse osmosis is not a viable solution to purify water globally until the membranes and pumps can be made more cost-effective and point-of-use devices are invented that can be reused.

Another effective way to filter water is by distillation (18). This involves boiling water, creating steam, and then re-condensing the steam back to water. While this method is more efficient than many other methods at removing chemical, microbial, and physical contaminants, it requires fuel, is time intensive, and requires the use of several sterile containers, costing more money than is available to many of the households that are in need of purified water (16,18,23).

Two other, less frequently used, ways to purify water include the application of ultraviolet (UV) light and exposure of the water to sunlight (18). In most communities that require purified water, UV lamps are either not available or are too costly (16,18,23). For the communities in need, with an average time of six hours for water purification to take place, sunlight purification is too inefficient and inconsistent (16,18,23). Lastly, both of these methods do not work on turbid water (water with physical contaminants), thereby significantly reducing their practical application (18).

Materials and Methods:

For the purpose of scientific simplicity, this research paper will utilize select contaminants from the EPA standard, which ensures that drinking water will not pose a major health risk, thus meeting the global standard (Table 1). The contaminants chosen were chlorine, bacteria, nitrates, nitrites, lead, copper, hardness, iron, and dissolved solids. Other than hardness and dissolved solids, all of these are some of the most common drinking water pollutants, including bacteria, which are one of the most dangerous drinking water contaminants (6, 7). Hardness and turbidity are both used here as easy-to-test general surrogates of the levels of other contaminants that cannot be tested for as easily. A turbidity limit of 800 ppm was retrospectively considered to be acceptable based on a value of 753 ± 10 ppm capable of meeting the standard for potable water (see Table 3 in Results and discussion). It must be emphasized that this turbidity acceptance level is arbitrary and is not comparable to the EPA's < 0.5 National Turbidity Units (NTU) guideline.

Contaminants	pH	Bacteria	Chlorine	Nitrates	Nitrites	Lead	Copper	Turbidity	Hardness	Iron
Maximum Safe Level	6.5 to 8.5	$<10^2$ CFU/ml	10 ppm	10 ppm	10 ppm	0 ppm	1.3 ppm	800 ppm	120 ppm	0.3 ppm

Table 1: Water potability standards, bacteria: CFU/mL, all others: ppm

Figure 1: The pond in Poughkeepsie, NY

Purification Method	Cost (USD)
Aquatabs® (Pack of 2), Medentech Inc., Wexford, Ireland.	$2.00
Mussels or Oysters (Obtained from a local market in New York City, New York, 1 each)	~$1.50, price varies by region
Chlorine (per 5 drops, purchased from a local pool store)	$0.25
UV light (flashlight), Amazon.com	One – time $50 cost, $0.01 for later uses
Boiling	$0, significant variable cost in person-hours and for firewood
Solar Heating (Mylar and cardstock) , Amazon.com	One-time $20 cost
Cheesecloth (1 5" x 5" square), Amazon.com	$0.50
Coffee Filters (1), Amazon.com	$0.01

Table 2: Table of purification methods and costs

In this study, 0.5 L water samples were purified using commercially available Aquatabs®, addition of a single mussel or oyster and allowing them to filter feed in the water for three hours, addition of chlorine, directed UV light, boiling, solar heating, filtration through a cheesecloth, and filtration through coffee filters.

These methods, and their combinations (Table 2), were tested using water from different sources. All of these methods (and their combinations) cost less than $5 for running costs, making them less expensive when compared with many presently available methods. First, control samples were prepared by testing water from the following four sources: tap water from Hanoi, Vietnam, tap water from Manhattan, New York City, tap water from Poughkeepsie, New York run through a commercial reverse osmosis system, and water from a natural pond in Poughkeepsie, NY (Figure 1). The water samples were manually collected and hence source verified. The sampling procedure used to collect tap water involved a glass bottle (in order to reduce the risk of adding in plastics that could potentially affect the turbidity) filled to a predetermined level, and placed in a dark, room-temperature bag for transport. The sampling procedure for the pond was similar, but used a larger, plastic container instead, and water was transferred into it using a smaller plastic container.

Figure 2: The solar reflector used in the experiment. Water samples, in a clear glass bottle, were placed on the Mylar square in the center foreground of the image

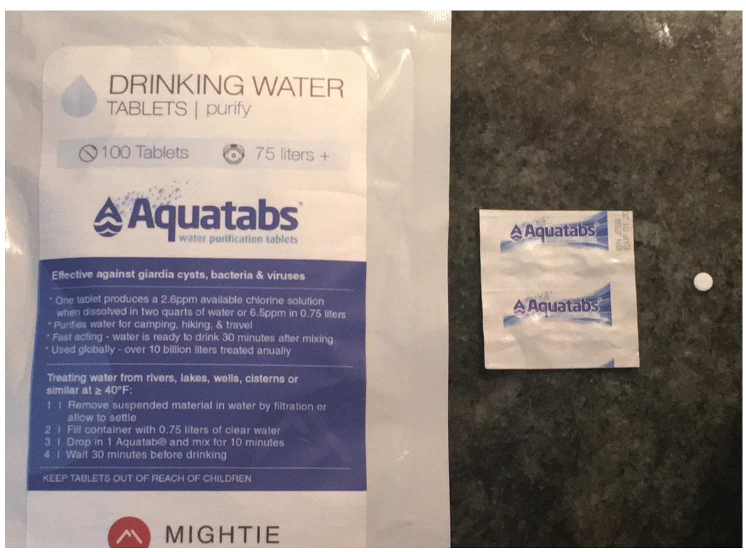

Figure 3: Aquatabs® commercial purification tablets

Next, 55 test samples were filtered, including samples from all four sources. Each sample contained 0.5 L of water. No sample used more than one non-physical filtration method, as combining these would increase costs. As the study progressed, it became apparent that the addition of ¼ tsp of pool chlorine resulted in a free chlorine level that was greater than the EPA limit, so five drops of chlorine (~1/20 tsp) were substituted to ensure compliance. To determine the effect of the coffee filters, additional coffee filters were added in pairs (a maximum of 8 coffee filters were used because the water did not percolate through 10 filters). Initially, the intent was to test multiple layers of 10 cm^2 cheesecloth. However, since preliminary experiments determined that water could not penetrate two layers of cheesecloth, this line of experimentation was discontinued. The solar reflector was constructed of Mylar (biaxially-oriented polyethylene terephthalate) on a cardstock frame (Figure 2). The UV experiment utilized a short-wave UV light, with wavelengths closer to the X-ray end of the UV spectrum than the visible light end. The mussel and oyster experiments were performed using a single mussel or oyster for the 0.5 L sample, regardless of the organisms' size.

Figure 4: Baldwin Meadows water quality testing strip bottle

Figure 5: Digital turbidity meter. Model is a TDS-3, made by HM digital, Vista, CA.

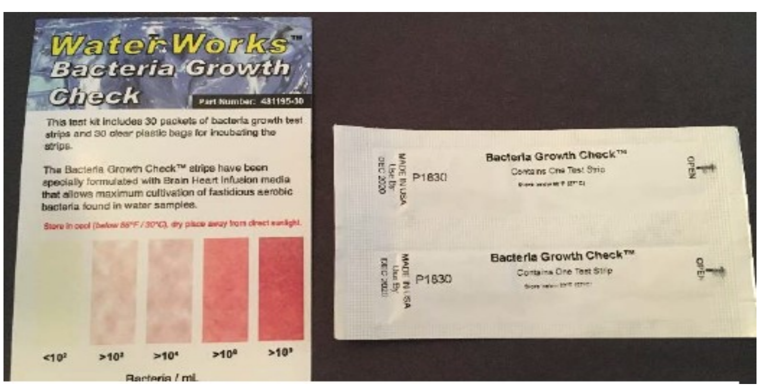

Figure 6: Water Works bacteria growth test strip, Industrial Test Systems Inc., Rock Hill, SC.

A Baldwin Meadows water quality strip (Figure 4) was used to test for hardness, chlorine content, iron content, copper content, lead content, nitrate content, nitrite content, pH, and alkalinity. The water quality strip was immersed in the water for 2 seconds, removed, dried and read. The pH test strip readings were calibrated using standard pH solutions of 3.0, 4.0, 5.0, 6.0, 7.0, 8.0, and 9.0. A turbidity meter (Figure 5) was used to measure sample turbidity (the amount of particulates present). The values were read at one, two, and three seconds. This was done three times because the turbidity fluctuated considerably, and more testing reduced the variability. A Water Works bacteria growth test strip (Figure 6) was placed in the water for two seconds, removed, and then placed in a near-vacuum sealed bag. To form a near-vacuum seal on a zip-top plastic bag, the bag was sealed leaving a small gap, then submerged into water until the zipper was just above the water line, after which the bag was completely sealed. The water pressure forced any remaining air out of the bag, thus creating a near-vacuum environment. The near vacuum sealed bag was immersed in a 30° C water bath for 48 hours, and the order of magnitude of bacteria/mL was visually estimated. Finally, the purification method that best cleaned the water (defined as the difference in the various attributes between the control sample and the test sample) was determined.

The water sources, storage, and purification methods not using mussels or oysters were similar across all samples. Unpurified water from each source was used as a control.

In addition, a series of control experiments was performed to determine that the bacterial growth check strip results were independent of pH. This was done by adding a bicarbonate buffer solution to the growth check medium after it had been dipped in a water sample to stabilize the pH, and comparing it to the sample's (naturally) differing pH. Another experiment was performed to determine that bacterial growth check strip results were not affected by the presence of other compounds (including chlorine, iron, and copper). This was done by comparing the results from identical bacterial growth check test strips dipped in pond water, with the exception that one of the test strips was post-rinsed with distilled water. A final control experiment was performed measuring the turbidity of tap water in one of the plastic containers with the same sample stored in a glass container to ensure that the method of sample storage did not affect the turbidity.

Results and Discussion:

The bacterial growth strip results were found to be independent of the pH of the water as well as not affected by the levels of the other water contaminants such as chlorine, iron and copper. There was no significant difference between the turbidity of the water sample stored in either a plastic or a glass container.

Experimental Composition	Turbidity (PPM) Mean of Three Tests	Hardness (PPM)	Chlorine (PPM)	Copper (PPM)	Lead (PPM)	Iron (PPM)	Nitrate (PPM)	Nitrite (PPM)	Alkalinity (PPM)	pH*	Bacteria Count	Does it Meet EPA Standards?
Poughkeepsie	7.5±10	25	-	-	-	-	-	-	40	6.4	<10e2	Yes
NYC	120±10	60	-	-	-	-	-	-	40	6.4	<10e2	Yes
Hanoi	138±10	120	-	-	-	-	-	-	80	7.2	<10e2	Yes
Pond	1060±10	120	-	1	5	-	50	10	180	9.0	>10e9	No
Pond, 1/4 tsp chlorine	1295±10	250	20+	-	-	-	-	-	40	9.0	<10e2	No
Pond, 5 drops chlorine	1125±10	160	5	-	-	-	-	-	80	8.2	>10e2	No
Pond, 2 coffee filters	937±10	120	-	-	-	-	50	10	40	7.6	>10e9	No
Pond, 5 drops chlorine, 8 coffee filters	792±10	120	-	-	-	-	-	-	60	7.4	>10e2	No
Pond, 2 Aquatabs®	1060±10	120	10	-	-	-	-	-	80	8.2	<10e2	No
Pond, 2 Aquatabs®, 8 coffee filters	753±10	120	-	-	-	-	-	-	40	7.3	<10e2	Yes
Pond, 1 cheesecloth	1160±10	120	-	-	-	-	50	10	40	8.2	>10e9	No
Pond, 3 hr mussels (A)	1170±10	120	-	-	-	-	-	-	60	7.2	>10e2	No
Pond, 3 hr mussels (B)	1140±10	120	-	-	-	-	-	-	40	7.6	>10e2	No
Pond, 3 hr oysters (A)	1260±10	120	-	-	-	-	-	-	40	7.2	>10e2	No
Pond, 3 hr oysters (B)	1175±10	120	-	-	-	-	-	-	60	8.2	>10e2	No
Pond, UV (5 min.)	1000±10	120	-	-	-	-	-	-	80	7.6	>10e4	No
Pond, boiling (1 min.)	1250±10	120	-	-	-	-	-	-	60	8.2	>10e2	No
Pond, boiling (1 min.), 8 coffee filters	785±10	120	-	-	-	-	-	-	40	7.6	>10e2	No
Pond, 6 hr solar filtration	1135±10	120	-	-	-	-	-	-	40	7.6	>10e8	No
Pond, 3 hr mussels, 8 coffee filters	790±10	120	-	-	-	-	-	-	80	8.2	>10e2	No
Pond, 3 hr oysters, 8 coffee filters	770±10	120	-	-	-	-	-	-	40	7.2	>10e2	No

Table 3: Results of selected water sample experiments. Highlighted values indicate safe levels of contaminants. The safe level for turbidity is not an official standard and more of a general guideline (at 800 ppm), and lower turbidity is generally better. The variability in the turbidity is reported as a range. The temperature was 27°C. pH* values have a variability of ±1.0.

Several qualitative observations can be made from Table 3. The presence of coffee filters in the purification method generally decreased the pH of the water regardless of whether it was used in conjunction with other filtration method(s). A mechanism for this was not readily apparent. Turbidity reduction efficiency did not linearly decrease with addition of more coffee filters as evidenced by turbidity values of 1060, 937 and 792 ppm using 0, 2 and 8 coffee filters respectively. This implied that a larger number of coffee filters did not necessarily translate into a proportional decrease in turbidity. In this study, so long as the protocol incorporated bacterial reduction (chlorine, oysters, mussels or boiling) the initial turbidity of the sample had negligible effect on the bacterial growth reduction (> 10^2 from >10^9). However, the bacterial growth reduction was lesser when UV or sunlight was used in the protocol (> 10^4 and > 10^8 respectively). It may be speculated that turbidity decreases the incidence and penetration of UV rays or visible rays (sunlight) into the bacteria that are harbored either in, or obscured by the turbidity contributing particle. Sunlight or UV bacterial reduction methods may hence be more efficacious at a lower initial turbidity.

Some purification methods increased the turbidity probably by adding more dissolved particles, by removing some of the existing water and thus increasing their concentration, or by deagglomerating or disintegrating existing suspended solids into more, smaller sized particles. Boiling the water for 1 minute caused a bacterial log-reduction similar to contacting the water with either mussels of oysters for 3 hours. However, as mentioned before, boiling is an energy, cost and time intensive process requiring fuel, that is itself CO_2 emitting.

The results of this study showed that the only water purification method which produced water that met the EPA standard was the addition of Aquatabs® in conjunction with filtration using 8 coffee filters (Table 3). However, boiling, addition of mussels or oysters, and addition of 5 drops of chlorine when combined with 8 coffee filters all also significantly reduced the bacterial concentration and the turbidity, when filters were used. Even though incubation with oysters or mussels did not render the water potable, it is encouraging to note that these filter feeding organisms caused a 7-log reduction in bacterial bioburden regardless of initial turbidity. It may be possible to produce potable water by increasing the duration of contact or by increasing the ratio of number of organisms to the volume of water. However, bivalves have a limit on how much water they can filter without their digestive glands becoming saturated with bacteria and viruses (25). In addition, they may also secrete out undigested micro-organisms as feces or pseudo-feces (26). Lastly, their reproductive potential, measured as larval survival, decreases with digestive gland saturation. Hence, while these filter feeders can be harvested to purify water, there are biological, environmental and bio-engineering limitations associated with their use. Some of these can be alleviated using shellfish farms and aquaculture, which are currently the fastest growing food production activities in the world (27). However, a deliberate concerted effort to combine aquaculture and water purification does not yet seem to exist at scale.

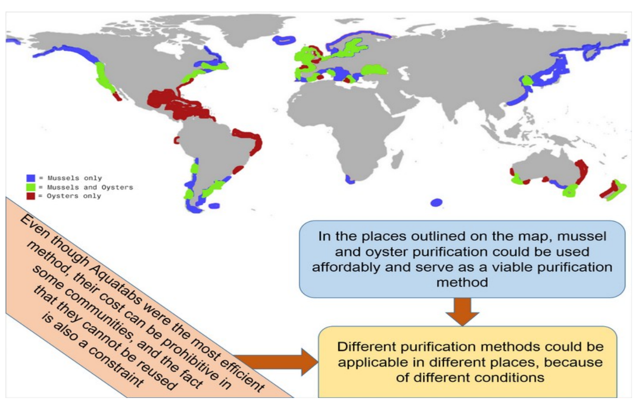

Figure 7: Map of bivalve growth locations, with notes on key takeaways. Data taken from (24)

Limitations

This study did not test all of the potential water contaminants listed by the EPA, merely a collection of some of the most common ones, and the contaminants that were tested for did not include fungi, spores or viruses. A turbidity of < 800 ppm was retrospectively defined as acceptable and bore no correlation to the EPA turbidity limit of < 0.5 NTU. The pond samples possessed natural variability, especially in turbidity and probably in the number and type of micro-organisms. Varying mussel and oyster weights were another limitation, although that may not have been a limiting factor considering the ratio of their weight to the volume of the water sample. The tests used were imprecise; with the variability in pH being ± 1.0 pH unit and that in bacterial count being of an order of magnitude. This was due to limited availability, higher cost and greater ancillary equipment requirements associated with precision tests and/or equipment. Purification of water using mussels or oysters necessarily means that this method is only available and accessible to coastal populations.

Conclusion

After assessing the most effective purification method, the next logical step in the process to create a cheap, easily implementable purification system would be to study the effects of the results of this study in different parts of the world, such as using oyster-based purification in South American communities, where oysters are readily available (Figure 7). Another important step would be to perform testing with larger, more representative water samples, as different purification methods may be able to purify larger quantities of water more efficiently. Specifically, a given number of oysters or mussels may be able to clean a larger quantity of water, while other purification methods may require more cost or energy. The basic idea of biodynamic cleaning and the focusing on the use of local resources could help provide access to clean water for everyone.

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