billion bottle project

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**Chemical Engineering for Good Challenge**
**2017 Competition Submission**

University Name & Location: **Case Western Reserve University, Cleveland, Ohio**
Team Lead: [redacted]
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Team Lead Phone: [redacted]
Title of Submission: **Reusable Solar Water Disinfection Sensor**
Submission Type: __x__ Underutilized Technology ___ Technology Toolkit

*Recommendation of the application of a specific technology, available today, that is not currently utilized in ISP projects.*

**Submission Team:**

The undergraduate engineering team member of the Billion Bottle Project, a student-run nonprofit based in Cleveland, Ohio, prepared this proposal. Founded by first-year medical students two years ago, it is now a multi-disciplinary organization funded by organizations such as the Environmental Protection Agency and the Clinton Global Initiative. The organization combines the expertise of undergraduate and graduate business, medical, and engineering students with the shared goal of eliminating waterborne illness by improving access to clean drinking water. The engineering team is developing the sensor described herein to aid communities in areas that lack clean water infrastructure.

**A. Define the specific community problem being addressed**

The global water crisis continues to be a pressing health concern worldwide. Even though clean drinking water is defined as a human right, 1.8 billion people currently do not have access to purified water. Around 663 million of those people do not use any water treatment techniques [1]. The resulting waterborne diseases represent a significant public health threat in developing nations. Roughly four billion cases of diarrheal diseases are reported each year [2]. Our analysis demonstrates a correlation between access to improved water sources and per-capita diarrheal disease mortality on a nation-by-nation basis. We analyzed the global water

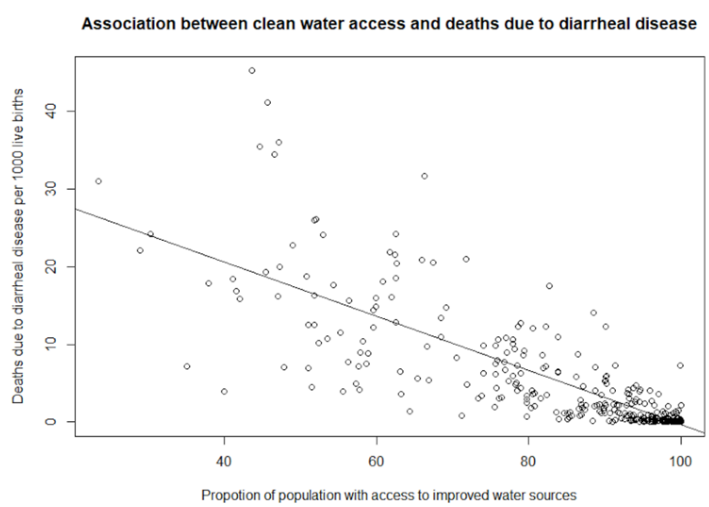


**FIGURE 1:** Nations with wider access to improved water sources tend to have lower diarrheal disease mortality rates, based on WHO data. Correlation between access to clean water and death due to diarrheal diseases gathered by Billion Bottle Project.

crisis data and found that there obvious direct correlation between unpurified water and waterborne illnesses, as illustrated in Figure 1. Combined with poor sanitation, waterborne illness accounts for 3.4 million deaths annually [3]. Waterborne illnesses are a tremendous burden on health infrastructure as well as over half the world's hospital beds are occupied by patients suffering from water borne illnesses [4].

Numerous methods of household water purification exist, each with benefits and drawbacks that lead to adoption based on the preferences and circumstances of individual households. However, the enormous gap in clean water availability around the world indicates that existing techniques and technology remain, by themselves, insufficient; however, the cost and lack of sustainable technology have caused a low acceptance rate in developing communities.

Of existing techniques, solar disinfection (SODIS) is one of the most cost-effective. Due to its incredibly low cost, wide applicability in global water-stressed regions, and extremely high efficacy in preventing waterborne illness, UV irradiation is a technology with great potential. Over five million people in 55 countries currently use UV irradiation as a their primary technique to purify water (Figure 2) [5]. However, some user feedback has questioned the efficiency and reliability of this technique [6].

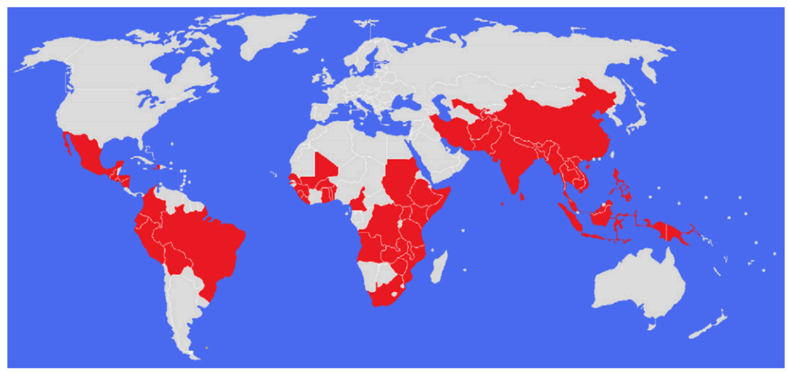

**FIGURE 2:** Countries where the solar disinfection technique is currently in use [5].

The solar disinfection technique requires only uses sunlight and plastic PET bottles. Users leave a bottle of contaminated water in the sunlight and the ultraviolet radiation kills the pathogens in the water in as little as six hours, making the water safe to drink as illustrated in Figure 3 [7].

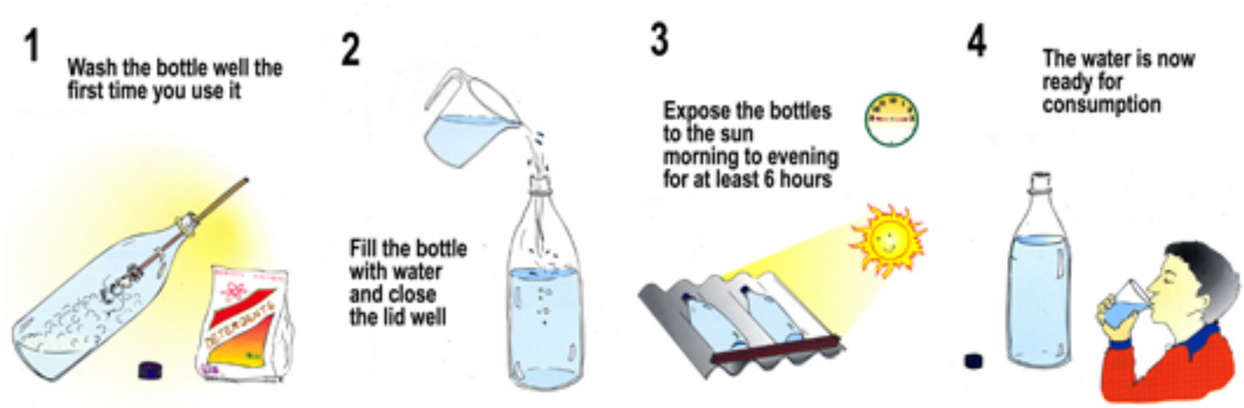


**FIGURE 3:** Solar disinfection method developed by EAWAG (1) Clean used PET bottle (2) Add contaminated clean water (3) Expose PET bottle to direct sunlight for at least 6 hours (4) Water is now purified [7]

The ultraviolet radiation can inactivate pathogens that cause waterborne diseases with high efficacy [8]. Research has shown that six hours under direct sunlight or two days in cloudy conditions is sufficient for purifying the water. Solar disinfection has been proven to significantly reduce waterborne bacteria including *E.coli*, *Y. enterocolitica*, *C. jejuni*, and *P. aeruginosa*, viruses including rotavirus and bacteriophage T2, fungal species, *C. albicans* and *Fusarium sp*., as well as the *Giardia* parasite [9][6]. For example, C. parvum, a common bacterium found in unfiltered water, was studied over a time and UV exposure range, which can be seen in Figure 4 [4]. This shows that UV light for a certain time period can successfully lyse the bacterium in unfiltered water.

The efficacy of the technique extends beyond the laboratory. In numerous randomized trials, UV irradiation has been shown to reduce the risk of contracting waterborne diseases. For example, it has reduced diarrhea incidence by 40% in Tamil Nadu, India, and reduced epidemic cholera infections by 84% in children in a Kenyan community [11][12].

While UV irradiation clearly shows great promise in reducing waterborne illness, educating communities on its use can be challenging. This difficulty stems from the complexity of solar disinfection guidelines, which demand that users compensate for myriad factors affecting ultraviolet exposure such as cloud cover, water turbidity, bottle size, and bottle material. Furthermore, negative attitudes toward solar disinfection can be caused by social factors, low user confidence in solar disinfection technology, and limited belief in the value of clean water [11][12].

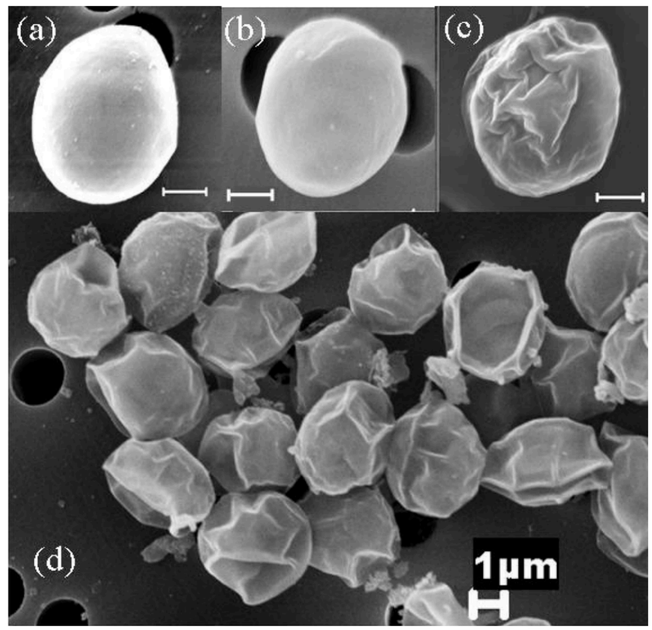


**FIGURE 4:** Scanning electron micrograph demonstrating lysis of C. parvum, a common bacterial pathogen, through ultraviolet radiation. (a) C. parvum at 40° C at time = 0 hours. (b) C. parvum at time = 10 hours (c) C. parvum at 870 W/m$^2$ at time = 10 hours (d) Cluster of C. parvum at 870 W/m$^2$ at time = 10 hours [4]

**B. Describe the specific technology and how it is based on chemical engineering principles, provide electronic copies of public links to references (papers, descriptions of commercial applications & offerings, patents, other supporting material)**

The goal of this project is to develop a reusable dye-based sensor to help drive adoption of solar disinfection. Users will simply drop the sensor into their PET bottle at the start of the treatment and the sensor will change color once the water has received enough ultraviolet radiation. The cost of the proposed device is under $1, making it far more affordable than

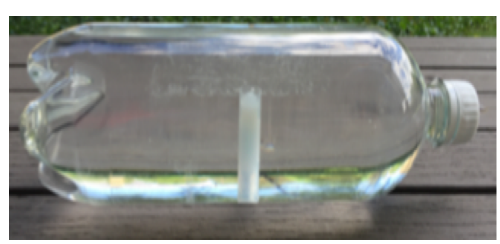

**FIGURE 5**: Testing the sensor (seen inside the PET bottle) in direct sunlight.

any competitor long-term. Such a device would be the first of its kind, greatly simplifying solar disinfection education by obviating the need for users to account for weather, water, and bottle factors to determine exposure time [13]. Eliminating all of those concerns is likely to improve efficacy, reliability, and user compliance. Through these benefits, the availability of such a sensor could make solar disinfection more accessible and more desirable, encouraging more households to use UV irradiation and thereby preventing waterborne illness.

There are two main categories of sensors currently under development for this application: photovoltaics and dyes. Existing sensors have a variety of shortcomings that the proposed design would address. Current sensors can account for weather changes, but do not adjust for bottle characteristics (e.g. size, thickness, material, and clarity) or water characteristics (e.g. turbidity, starting contamination level). Dye-based sensors are typically extremely inexpensive, but to date are only single-use, adding up to a prohibitive long-term cost. On the other hand, photovoltaic devices can be reused extensively, but have a prohibitive upfront cost. The most successful photovoltaic sensor, as well as the only one commercially available, is the WADI, which cost about $20. This increases the cost of solar disinfection by a factor of 30 [15] [16] [17]**.**

A sensor that combines the ultra-low-cost of dye-based sensors with the reusability of photovoltaic sensors would represent a tremendous leap forward for solar disinfection. The proposed design possesses not only these features, but is designed to be submerged in the bottle itself, allowing for exact UV dose measurement and therefore the most accurate assessment of treatment time.

A CAD model of the proposed sensor is shown in Figure 6. Without the sensor, users must (1) ensure the bottle is made of the correct material (2) make sure the bottle material is not too thick (3) make sure the bottle is not too big (4) check that the water is not too turbid (5) estimate the percentage of cloud coverage and use it to calculate the treatment time. However, by using the proposed sensor, users will only have to confirm that the sensor changed color to be certain the water is safe to drink [13].

**FIGURE 6:** CAD drawing of Billion Bottle Project's sensor

To use the device, the user submerges the sensor in a PET bottle filled with unpurified water and leaves the bottle in sunlight. As the bottle is exposed to sunlight, the chemical formulation inside the device gradually changes color until it reaches the endpoint color, which indicates that the UV treatment is complete and the water is safe to drink. Furthermore, the housing prevents the entrance of water into the device at all times; however, it does allow air to enter when the device is not submerged. This allows for the reverse reaction to occur, resetting the sensor for subsequent use. The overall solar disinfection technique with Billion Bottle Project's sensor is outlined in the **Figure 7** schematic.

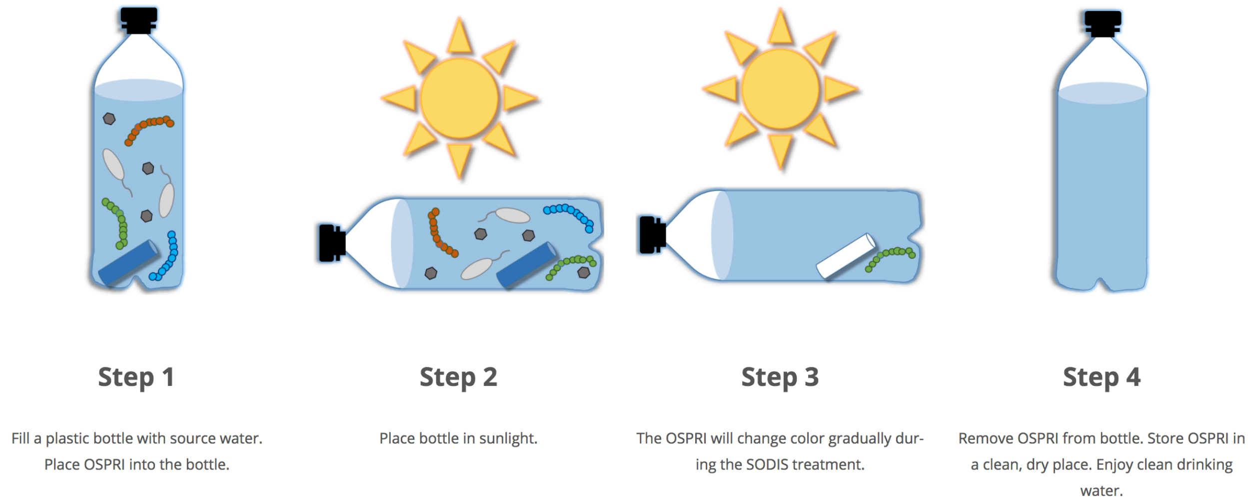


**FIGURE 7:** Stepwise schematic of the solar disinfection method with using Billion Bottle Project's sensor which shows the ease of use of the sensor

The chemical formulation within the sensor is based on existing technology used for UV dosimetry, oxygen sensing, and rewritable paper applications, among others. A similar chemical reaction described in the literature is shown in Figure 8 [18].

Overall, Billion Bottle Project's sensor has only a few main components that allows for easy synthesis and usability. First, the sensor device is composed of a non-toxic UV-sensitive formulation within a clear plastic housing as shown in Figure 9. The outer container permits visualization for the chemical formulation along with the color change.

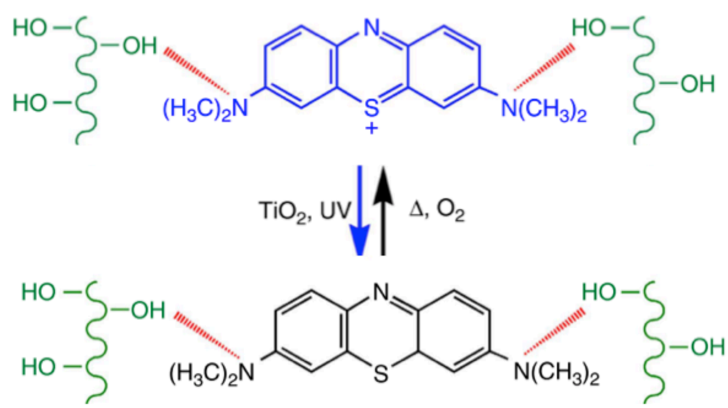

**FIGURE 8:** Reversible redox reaction involving the color switching of a solution composed of $TiO_2$, Methylene blue, and hydroxyethylcellulose [18]

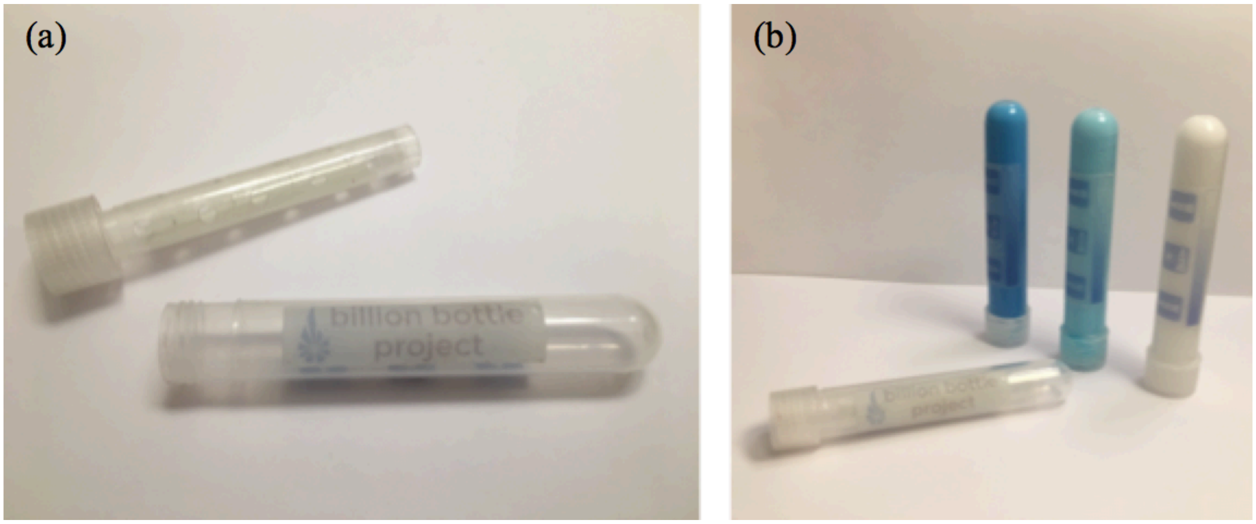


**FIGURE 9:** Sensor images with and without solution dye (a) Opened sensor component which shows transparency and easy usability along with oxygen permeability (b) Sensor color change with different UV radiation times (from no UV light (left) to full UV exposure (right))

The reversible color change of the chemical formulation is mediated by exposure to UV light (for the forward reaction, from the initial color to the endpoint color) and exposure to air (for the reverse reaction, from the endpoint color back to the initial color), as quantified in Figure 10.

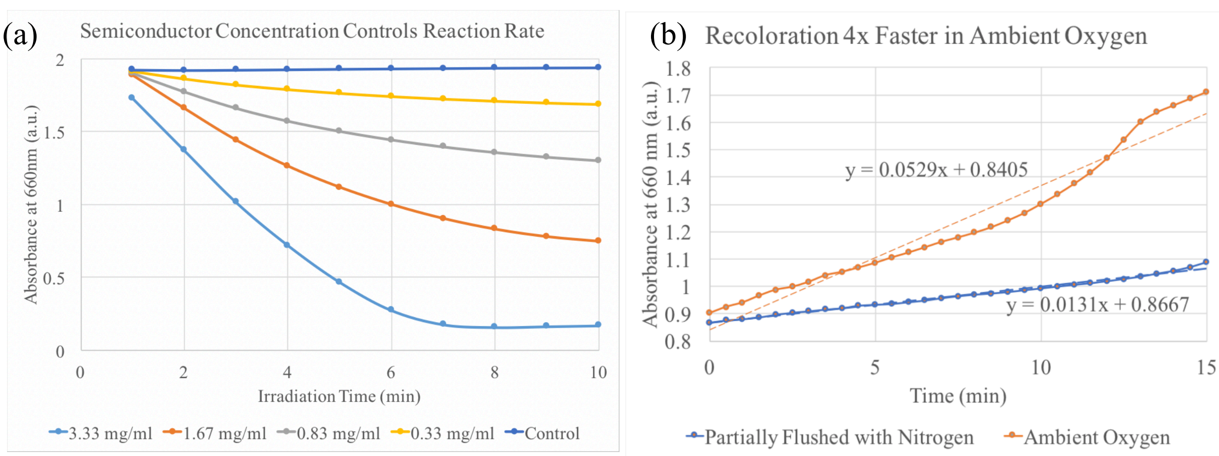


**FIGURE 10:** Changing the concentration of the semiconductor ($TiO_2$) within the sensor greatly influences the reaction rate and the time it takes the sensor to change color (a) Irradiation time versus absorbance at different concentrations of $TiO_2$ (mg/ml) (b) Concentration of oxygen and its effects on the recoloration of the sensor

The time course of the forward color change has a standard deviation no greater than 10% for at least 15 cycles. The time course of the forward color change (during the UV irradiation) is tunable within the range of 2-6 hours in direct sunlight. Overall, Figure 10 illustrates how the semiconductor within the sensor controls the overall reaction rate. Having a higher concentration allows the blue chemical formulation to change to white faster than smaller concentrations of $TiO_2$.

C. **Describe what kind of data would be required to design/customize this technology for ISP projects**

*i. Optimizing chemical formulation for SODIS treatment duration*

The most essential component of the sensor is the absorption and reversibility of the sensor solution. Since one of Billion Bottle Project's goals is to create a cheap and long-term detector, studying the absorption and reaction rates will give better data to prove the sensor's ability to last a year. This means that there is a prime wavelength for the color to change from blue to white. Billion Bottle Project's sensor uses this advantage in the sensor in order to make sure that the color change occurs when the water is fully purified.

To understand what exposure of oxygen is needed for reverting the color from white to blue it was necessary to study the absorbance as a function of time for different concentrations of oxygen. The engineering team looked at ambient oxygen and versus partially flushed oxygen with nitrogen. The results show that allowing the sensor to be completely exposed to oxygen significantly increases the reversion reaction rate. Furthermore, understanding how the chemical formulation reversion reaction rate is a function of absorbance is necessary to better control the properties and usability of the sensor.

*ii. Select Optimal Device Membrane*

For the sensor to revert back to its original color, oxygen must be administered into device. Therefore, an optimal device membrane needs to be designed that allows oxygen to enter the sensor after the color conversion occurs. Furthermore, the capsule must be mechanically durable and must not degrade in high temperatures. An example of a membrane that was used for one of the prototypes was a fish bag that allows only oxygen to permeate through the membrane. This was then placed within a small capsule that is durable, and can easily be opened/closed. For the future, Billion Bottle Project will look into a more durable way to encapsulate the sensor.

*iii. Quantifying Time for Solar Disinfecting to Cause Bacterial Death*

To customize the sensor, it is necessary to create a standardized model for measuring bacterial activation within the water. This is crucial because unlike filtration and chemical-based methods of water disinfection, solar disinfection does not affect the turbidity or microscopic appearance of bacteria in the water. This means that pathogens remain in the water either dead or critically damaged depending on how much UV exposure the bacteria has received. One way to quantify bacterial growth is to culture bacteria dilutions on agar to visibly determine the bacterial load. From quantifying this technique, Billion Bottle Project's engineering team can measure the kinetics of bacterial inactivation for the solar disinfection method. The data can then be applied to the formulations within the sensor to optimize and customize the overall sensor.

D. **Describe why this technology would be appropriate for implementation in partner communities. Include consideration of technical, financial, and cultural**

**sustainability. Provide estimated typical costs for initial installation, maintenance, and operation.**

The goals and key innovations of the proposed sensor, along with associated design tradeoffs, are described below.

*Lowest Long-Term Cost*

Because the sensor is a chemical dye sensor, it can be produced at an exceptionally low cost. The current bill of materials for the preliminary devices is $0.13 per device at a pilot scale, though this may increase with the incorporation of other additives to the formulation. While manufacturing and distribution costs will increase this per-device cost, the max price will be $1 at the production scale. While not as affordable as a single-use sensor, the sensor has drastically lower long-term cost (and a much lower reliance on a consistent distribution network) than single-use sensors. Similarly, the cost is at least one order of magnitude lower than the cost of photovoltaic devices, the nearest reusable competitors.

*Highest Accuracy*

No sensor exists to be placed in the UV irradiation bottle during treatment. The sensor's use of non-toxic dye formulation components enables it to be placed in the bottle. To further mitigate any toxicity risk, the dye will be contained in an insoluble polymer matrix and the sturdy device housing will be sealed. Because the device sinks to the bottom of the bottle, it receives exactly the amount of ultraviolet radiation that the water receives. Thus, while photovoltaic sensors correct only for weather-related differences in ultraviolet radiation, the sensor additionally corrects for water turbidity, bottle size, bottle material, and bottle wear.

*Minimal End-User Training*

Because solar disinfection users must currently be trained to recognize a large number of factors that may affect the effectiveness of UV irradiation, the use of solar disinfection is low and growing slowly. A value of the sensor's design is that it significantly reduces the solar disinfection training time; instead of relying on the user to control for every factor that affects UV dose, the sensor adjusts and only indicates a successful treatment once a worn bottle that is no longer transparent. A photovoltaic solar disinfection sensor placed outside the bottle, unable to sense any change, would indicate treatment completed before the water is safe to drink. Because the sensor is submerged inside the bottle, it sees the same radiation the water experiences and adjusts accordingly, reducing the burden on training sensors.

*Reusable*

Billion Bottle Project's sensor would be the first dye-based, reusable sensor. Reusability imparts lower long-term costs, making it economically feasibly to a wider population, and limits the waste associated with single-use sensors.

*Environmental Benefits*

The goal is to create a device that simplifies solar disinfection in order to encourage more people to use this sustainable technique of disinfecting drinking water. Doing so would prevent incidence of waterborne diseases that can lead to death. As a byproduct of promoting solar disinfection along with the sensor, there number of people using fossil fuels to boil water will decrease substantially. In return, this will reduce pollution along with provide an easy and affordable way to purify water.

*Overall Significance of OSPRI*

Billion Bottle Project's sensor is a unique and important add-on to the solar disinfection method that can increase the quality of lives in communities around the world. Implementing the sensor will lead to decreased cases of diarrheal diseases and will increase the access to clean water in communities that use solar disinfection as their primary treatment technique.

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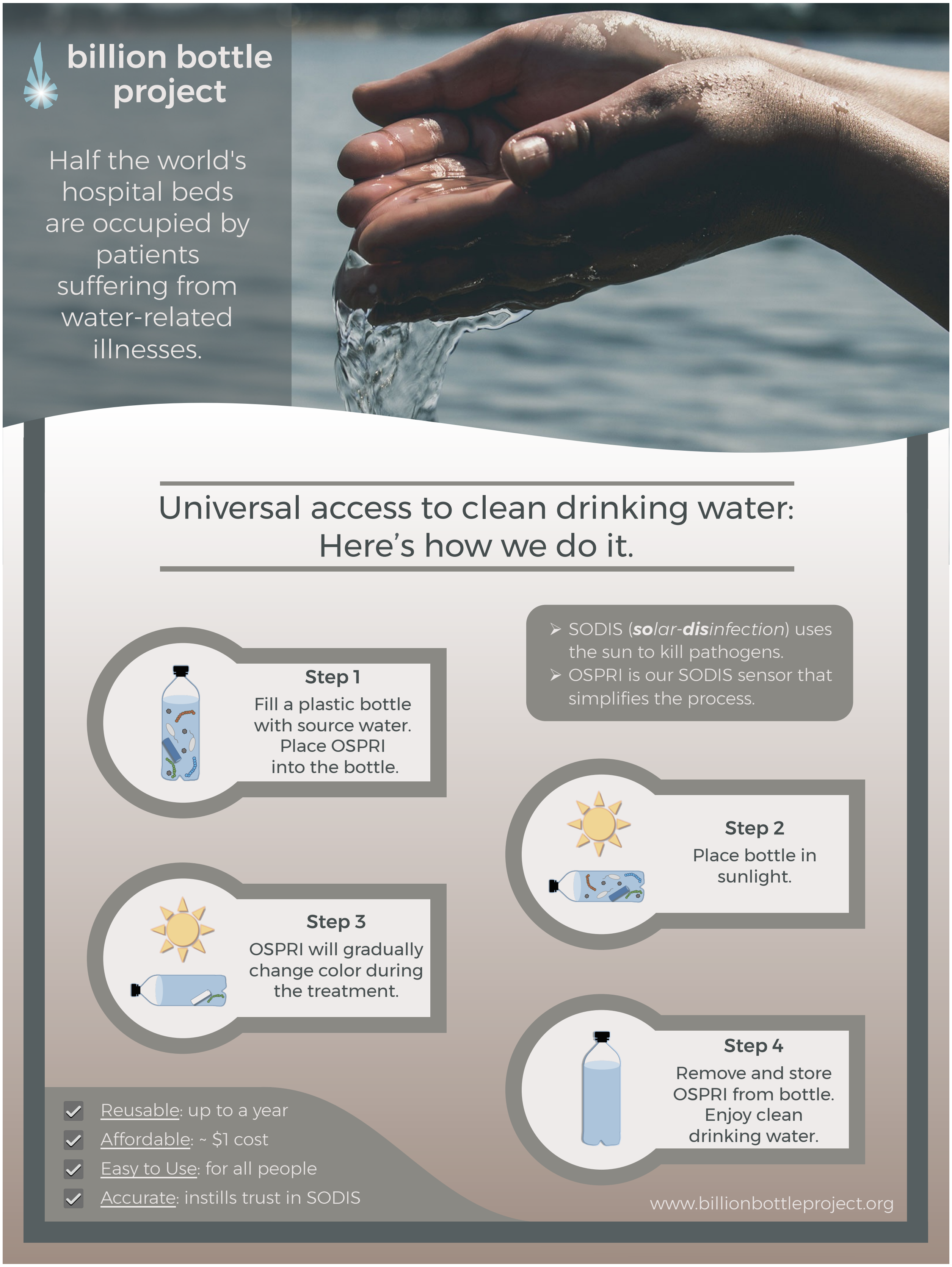
## Appendix


billion bottle project
Half the world's hospital beds are occupied by patients suffering from water-related illnesses.
Universal access to clean drinking water: Here's how we do it.
SODIS (solar-disinfection) uses the sun to kill pathogens.
OSPRI is our SODIS sensor that simplifies the process.
Step 1
Fill a plastic bottle with source water. Place OSPRI into the bottle.
Step 2
Place bottle in sunlight.
Step 3
OSPRI will gradually change color during the treatment.
Step 4
Remove and store OSPRI from bottle. Enjoy clean drinking water.
Reusable: up to a year
Affordable: ~ $1 cost
Easy to Use: for all people
Accurate: instills trust in SODIS
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