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Validation of the PATHOGENA Electron-Activated Reactor for Purifying Contaminated Water in the Parkersburg Area in West

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Abstract

This paper concerns validation of the PATHOGENA version of electron-activated reactors designed to purify contaminated water to make it potable. The basic design of PATHOGENA is a 100-gallon plastic tank batch reactor which houses a vapor-ion plasma (VIP) generator and 1-micron ion-separator (ION-SEP) porous water filter. While the VIP generator splits ambient air into aggressive water treatment agents in the form of charged ions, free electrons, hydroxyl and peroxyl radicals using UV radiation, the ION-SEP filter is designed to eliminate broad-spectrum bacteria and other microbes. The validation process was started with creation of water quality database from: (a) contaminated surface water; (b) EPA/West Virginia Water Quality Standards, and (c) Vienna City Council drinking water. The PATHOGENA purifier was then run 14 days/month from April-September 2014 and samples analyzed for chemical and bacteriological quality. When the results were matched against previous data, PATHOGENA compared favorably with both EPA/West Virginia water quality standards and Vienna City drinking water (R^2 = 0.99; p<0.011; N = 13). The study found PATHOGENA as an affordable technology capable of delivering clean water to households at about \$0.27 per person per day with economic savings of nearly \$7.00 at the same rate.

Keywords: Validation; PATHOGENA; Electron reactor; Contaminated water; Treatment; EPA water standards

Introduction

Nearly 800 million people representing 11% of the world's population have no access to good drinking water; 40% of this number lives in Sub-Saharan Africa [1]. Consumption of contaminated water leads to serious health problems in poor countries of which guinea worm infection, typhoid fever, cholera, dysentery, hepatitis and gardiasis are well-known. Aside from this, health experts are concerned about potential health hazards posed by consuming contaminated water; some health hazards are described in Table 1. The search for water from long distances (sometimes 5 miles away from home) also imposes health and economic burden on women and children who remain0020traditional water-finders in many poor countries [2,3]. The connection between bad drinking water and poverty in the developing world was one of the main reasons the United Nations launched the Millennium Development Goals (MDG) in 2000. An important goal of the MDG was that research and capital investment in global water supply should lead to 92% worldwide access to clean water by 2015; unfortunately, this target has not been achieved for most part of the developing world [1,3].

In countries where treated water is mainly available to the urban population, research is still needed to develop easy-to-operate and affordable water treatment systems to help deliver potable water to the majority of the population [2-4]. Since 2000, many papers have been published to document new water treatment technologies which can be categorized broadly as follows: (1) chemical water treatment systems (e.g. chemical treatment, ion-exchange and oxygenation), and (2) mechanical water treatment systems (e.g. separation, filtration, radiation, etc.) [5]. Speaking about wider coverage, technology affordability and uptake in the developing world, non-chemical treatment systems like gaseous ozone, visible/UV photocatalytic disinfection, ion-exchange resins, carbon-fiber filtration and free-electrons exposure seem to be reasonable ideas [5-13]. This explains why the PATHOGENA free-electron-activated system (Figure 1) is the subject of this study.

The PATHOGENA water purifier has proved successful at cleaning contaminated water at the Denver Memorial Hospital, MIT Nuclear Reactor Lab and US Navy Shipyard Storm water; part of which is reported by [14]. The uniqueness of this study is validation of the domestic version of PATHOGENA, for which we hypothesize the reactor's capability of purifying and delivering potable water at an affordable price to local people in poor countries. Specifically, this paper is aimed at examining PATHOGENA's water purifying capability and affordability at the poor village level.

The study area

The inventor and patent-holder of the PATHOGENA electron-activated reactor is Dennis Johnson of the EcH_2O Group (Colorado) but through collaborative permission, this validation was implemented at the Ohio Valley University in West Virginia (Figure 1). The Ohio Valley University is a small, liberal-arts baccalaureate college located in the Wood County of West Virginia. The Wood County (US Census population for 2010 = ~87,000) is home to the mid-Ohio River valley, where the Ohio River drains downstream serving as the boundary between the States of West Virginia and Ohio (Figure 1). The Little Kanawha River serves as the main tributary of the Ohio River in Parkersburg; which in turn is fed by small streams like the Pond Run. The geology of the area is typified by highly permeable sand and gravel glacial outwash deposits whose high-yielding aquifers partly serve the water needs of the local population [15]. Surface and groundwater

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Contaminants			Source of Contamination	Potential Health Hazard
Inorganic Contaminants		Fluoride	Erosion of natural deposits; water additive to promote strong teeth; discharge from aluminum and fertilizer plants	Bone tenderness and pain
		Nitrate	Runoff from fertilizer use; leaching from septic tanks; sewage sources; discharge from natural deposits	Respiratory and spleen infection; increased risk of cancers; dysfunction of thyroid gland
		Lead	Discharge from water service lines; leakage from plumbing fittings in old houses	Liver and kidney damage (especially pregnant women and children); increased risk of cancers
		Arsenic*	Discharge from mining and chemical plants; leakage from oil and gas wells	Damage to heart, liver, bladder and kidney; impaired central nervous system
Organic Chemical Contaminants	Volatile	Chlorine	Water additive used to control microbes; septic tanks	Eye and nose irritation; stomach discomfort
		Haloacetic acids	By-product of drinking water disinfection; urban storm water runoff	Increased risk of cancers; liver and kidney disease
		Total trihalomethanes	By-product of drinking water disinfection; septic tanks; urban storm water runoff	Increased risk of cancers; liver and kidney disease
	Synthetic (mainly pesticides and herbicides)	*Examples:* Atrazine, rotenone, paraquat, dibromochloro-propane, etc.	Agriculture; residential uses; urban storm water runoff	Increased risk of cancers; liver and kidney disease; key endocrine (e.g. estrogen) disruptors – Rotenone and paraquat have been associated with Parkinson's disease (*Tanner et al. 2011*)
Microbial contaminants		Viruses, bacteria, protozoa and parasites, e.g. *Giardia limblia*	Human and animal waste; sewage system	Gastrointestinal illness (mainly diarrhea, vomiting and cramps); headaches
Radioactive contaminants*		*Examples:* Radon gas, Radium (226/228)	Groundwater; oil and gas wells; radon leakage from homes	Increased risk of lung cancer

NOTE: The parameters marked (*) were studied because of lack of laboratory resources and will be addressed in the next study.

Table 1: Key water contaminants matched against potential health hazards.

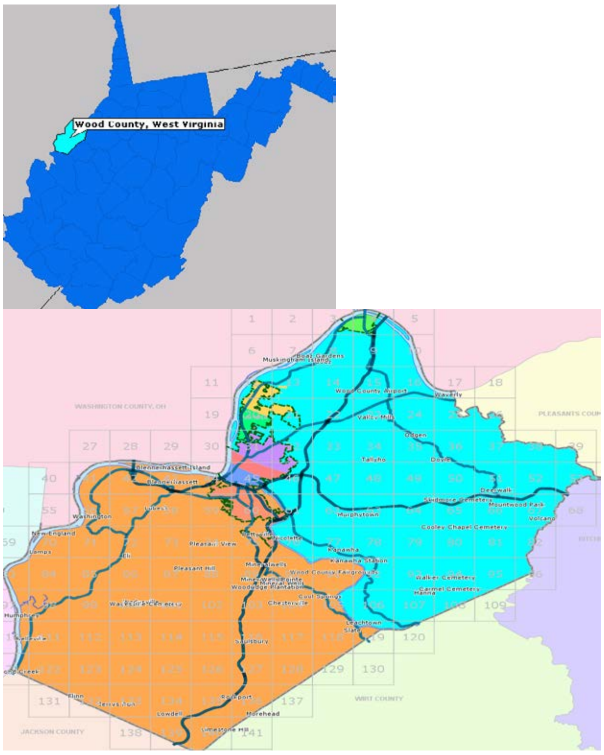

Figure 2: (*Top*) Map of West Virginia showing Wood County study area. (*Bottom*) Map of Wood County; notice that the Ohio River runs downstream from the northwestern part serving as boundary between the States of West Virginia and Ohio. Contaminated water samples were collected from the Ohio River, Pond Run stream and Twin Lakes in grid 20 of the bottom map (Source: OnlineGIS.net, 2015).

pollution is well-documented by authors like Kozar and McCoy [15], Foreman et al. [16] and Lutterel [17]. These reports show that water pollution in the area comes mainly from surface runoff across the district's rural ecosystem, discharges and occasional effluent spillages from local chemical industries.

Materials and Methods

Materials

The PATHOGENA electron-activated reactor (Figure 2) consists of: (1) 100-gallon plastic tank batch reactor; (2) VIP generator; and (3) 1-micron ION-SEP porous water filter. The VIP generator has fabricated seat on the tank cover while the filter is fitted about 10 inches above the base of the tank. The filter is connected to a fine bubble infuser using a 1/2-inch rubber hose (Figure 2). The principal component of the generator is UV radiation lamp (λ = 155nm) capable of splitting ambient gases (i.e. O_2, N_2) into monatomic charged particles using ultraviolet ionizing energy and magnetic emission. The filter is a high quality polarized media designed to eliminate bacteria and remove de-scaled and coagulated solids and debris.

Methods

There are multiple ways of performing industrial and technology process validation tasks, some of which are critically reviewed by Vandervivere et al. [18]. In this case, a modified version of the US Federal Drugs Authority (FDA) approach was adopted [19]. The tenets of the FDA guidelines on technology process validation (Long et al. [19]) is that validation should involve multiple test-runs, analysis of test-runs and statistical correlation with standardized processes or globally-tested products. If we consider, for instance, a brand new chemical product, successful runs of three consecutive product batches against a standard or well-known product may be viewed as validated.

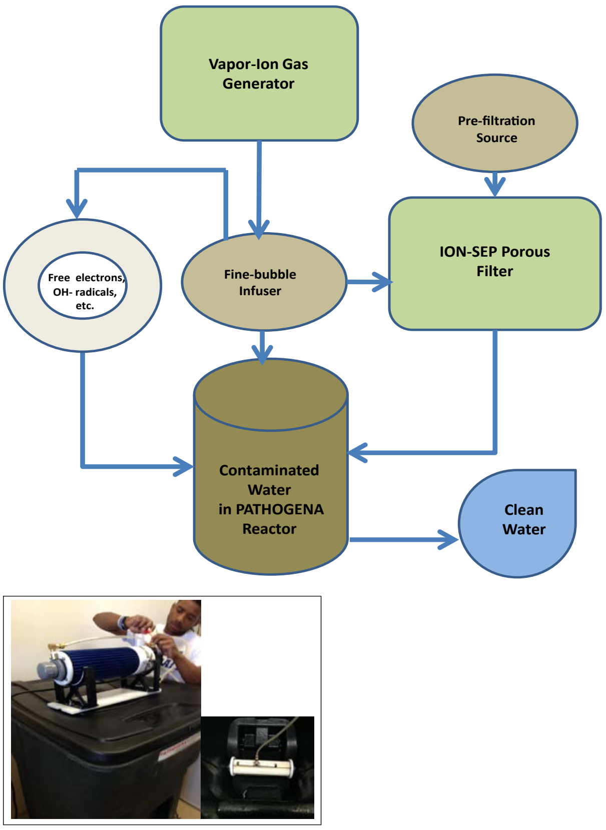

Figure 2: Schematic of the PATHOGENA electron reactor. The inset (below) shows the VIP generator on top of the reactor tank and ION-SEP filter at the base of the tank.

It is against this background that the PATHOGENA water filtration was analyzed qualitatively and quantitatively, and matched against published standards as described below.

First of all, a chemical and bacteriological database was created from weekly analysis of untreated water collected from the Ohio River, Pond Run stream and Twin-Lakes pond (Parkersburg area) April-August, each in 2013 and 2014. The Vernier LoggerPro-3 analytical procedures were used for chemical analysis and results matched against UN/WHO, US/EPA and West Virginia water quality standards [20-22] (Table 2). Again, the US/EPA method for determining organic compounds in drinking water [23, 24] was applied. First, analytes were extracted by passing 1L of sampled water through solid matrix with a chemically bonded carbon organic phase (liquid-solid extraction, LSE). The organic compounds were eluted from the LSE disk with small quantities of ethyl acetate followed by methylene chloride, and the extract concentrated by evaporating the solvent. The sample components were separated, identified, and measured using PerkinElmer's GC/MS-580 instrument. Compounds eluting from the GC column were identified by comparing measured mass spectra and retention times to (online) public domain spectral library.

One of the most widely used methods for bacteriological analysis is the multiple-tube MacConkey's broth culture and fermentation technique [23, 25-28]. Here, a modified version was adopted where bacteria colonies were grown using agar media and analysis performed using the most probable numbers technique; the results were verified using Macrady's probability tables [29,30].

Next, the PATHOGENA reactor was run daily (water treatment cycle) at weekly intervals while samples were tested in the first hour and every six hours subsequently for two weeks. The purpose was to test duration for the reactor's treatment of contaminated water (i.e. residence time) and optimize water sampling time. The PATHOGENA results (Table 2 and Figure 3) were then validated against local database and published data [22,29,31,32]. The detailed process chemistry of the PATHOGENA electron-activated reactor is described by Dennis [30]. Here, a summarized version is presented as follows:

Ionization of atmospheric oxygen: Using a UV light source, magnetic energy (MagE) was used to split atmospheric oxygen producing charged particles with ultimate release of superoxide ion and ionized singlet oxygen.

Water Quality Parameters	Ohio River	Pond Run Stream	Twin-Lakes Pond	EPA/West Virginia maximum contaminant level (MCL)
pH (-)	6.7-8.0*	6.2-7.8	6.1-8.2	6.0-8.5
Turbidity (NTU)	13.4	15.2	18.7	<1.0
Fluoride (ppm)	3.6	Trace	5.1	4.0
Salinity (µS/cm)	128.1	130.2	133.6	<80.0
Calcium (ppm)	6.8	4.9	6.2	6.0
Nitrate (ppm)	11.7	18.1	16.6	10.0
Potassium (ppm)	3.8	7.0	6.9	5.2
Dissolved oxygen (ppm)	18.1	6.2	1.7	>15.0
Total dissolved solids (ppm)	60.9	67.6	70.1	50.0
Total haloacetic acids & halomethanes (ppb)	Trace	Trace	1.2	<0.07
Heavy metals (Pb) (ppb)	Trace	Trace	Trace	0.00
**Total coliform (fecal & E. coli) (ppm)	Present	Present	Heavily present	0.00

***NOTE**: The data presented here are average values calculated for April-August 2013 and 2014. **Because total coliform count is quite difficult and prone to errors, the EPA recommends the presence/absence maximum contaminant level procedure.

Table 2: Water quality of Parkersburg water sources matched against EPA standards.

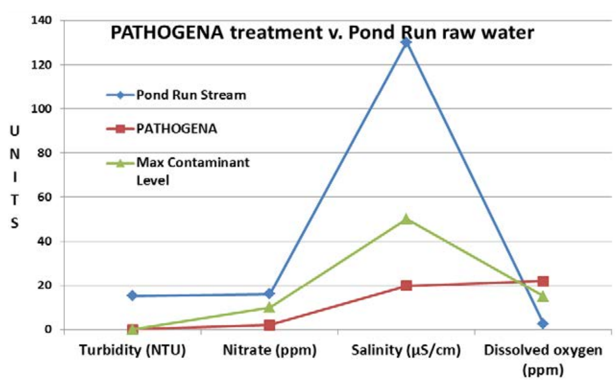

Figure 3: PATHOGENA electron-treatment matched against untreated water (Pond Run stream) and verified using EPA water quality data (Maximum contaminant level).

Note: Lower dissolved oxygen is more detrimental to water health than benefit.

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$$O_2 \xrightarrow[MagE]{UV} O^{\alpha+} = O^{\alpha-} \xrightarrow[MagE_{O^-_2}]{UV} O_2^-, O_2^2 \leftrightarrow O^0 - O^0 - (singlet\ oxygen) \quad (1)$$

Ionization of atmospheric nitrogen: Similarly, UV radiation was used to split atmospheric nitrogen to release charged nitrogen particles with release of free electrons (e-), which accelerates oxygen ionization.

$$N_2 \xrightarrow[MagE]{UV} N^{\alpha+} = N^{\alpha-} \xrightarrow[O_2 ionized]{e^-} (free\ electron\ [e^-]\ plus\ accelerating\ ionized\ O_2) \quad (2)$$

Intermediate ozone formation and superoxide ion formation: Oxygen radiation leads to the production of ozone vapor, ionized ozone and superoxide ions, which can also dissociate into more singlet oxygen (see eq. 1 above).

$$O_2 \xrightarrow[MagE]{UV} O_3 \xrightarrow[MagE]{UV} O^+{}_3 \leftrightarrow \xrightarrow[MagE]{UV} O_2^- (superoxide\ ion) \quad (3)$$

Singlet oxygen interaction to form chain reaction ionized oxygen: Excess singlet oxygen can then produce a chain reaction of high energy ionized oxygen.

$$O - O^- - + xO^- - O^-(singlet) - \frac{UV + electrons}{MagE} {}^-O - {}^-O - {}^-O(-O_x^-) - {}^-O - (chain) \quad (4)$$

Generation of activated (ionized) steam vapor: Water reaction with singlet oxygen (or chained ionized oxygen) can produce high concentrations of hydrogen peroxide and/or hydroxide ions as saturated water produces excess peroxyl-reactive (oxidizing, disinfecting and coagulating) ionized water.

$$xO_2^- + H_2O \xrightarrow[steam]{e^-} xH_2O_2 \leftrightarrow xOH^- + xOH_2^-(scavenger) \quad (5a)$$

$$O_2^- + H_2O \xrightarrow[MagE_{\Delta T}]{e^-} H_2O_2 \quad (5b)$$

Generation of trioxidane steam vapor: Thermal reaction of hydrogen peroxide and ozone reacts can release free electrons, and potential production of trioxidane (eqn 6a), superoxide ions and peroxone (eqn 6b). Further reaction between charged nitrogen and superoxide ions in aqueous solution does not only produce aggressive free electrons but also dinitrogen tetraoxide (nitroxyl ions) and hydroxide ions toxic to microbes.

$$H_2O_2 + O_3 \xrightarrow[MagE_{\Delta T}]{e^-} H_2O_3 + O_2^- \quad (6a)$$

$$O_3 + H_2O_2 \xrightarrow[\Delta T]{e^-} H_2O_5 \quad (6b)$$

$$N_2^+ + 3O_2^- + 2H_2O \frac{e^-}{MagE_{\Delta T}} {}^-O_2 - N_2^+ - O_2^- + 4OH^- \quad (6c)$$

Results and Discussion

Table 2 summarizes contaminated water data archived for summer of 2013 and 2014. The turbidity, nitrate and salinity data (Table 2) particularly confirms previous reports that raw water pollution is a problem in the study area [15-17]. Nitrate contamination for instance, is not unexpected given the district's widespread wildlife (deer, wild geese, turkey, etc.) coupled with surface runoff from agricultural farms and home gardens.

But still, two fundamental questions remain to be answered: (1) how efficient is the PATHOGENA water purifier- in terms of decontamination and time of clean of water delivery? And (2) how affordable is the PATHOGENA system for poor rural folks especially in the developing world? The PATHOGENA was first matched against untreated water data and verified using EPA drinking water standards; Figure 3 presents the results. The results show how well PATHOGENA decontaminate raw water and closely satisfy EPA standards. Turbidity and salinity were tested in Table 2 given their distinct results. To determine the time it takes PATHOGENA to deliver clean water, testing was done one hour, and every six hours thereafter for 168 hours (28 tests /week). A summary of the results are presented in Figure 4. The treatments after the first hour did not give clearly positive results; but notice significant improvement in water quality after six hours in Figure 4. The next study will test an improved (more powerful) version of vapor-ion plasma generator to help reduce the PATHOGENA's residence (treatment) time to about 1 hour. Also, field validation in a developing country will help to confirm current findings; plans are being made to achieve this.

An important question is microbiological quality of PATHOGENA treated water. Previous studies by Pham Thuy et al. [33], Langlais et al. [34], Wolfe et al. [35] and Taylor et al. [36] have reported microbial inactivation from electron-bombardment, free radical attack and ozone and peroxone toxicity (peroxone is a mixture between ozone and hydrogen peroxide - eqn. 5). The theoretical basis is that heavy oxidizing agents like peroxides, peroxones and trioxidanes (eqn. 5-6) are capable of breaking down functional proteins of microorganisms through attack on cytoplasmic membranes [30, 34-36]. Wolfe et al. [35] for example, have reported the possibility of destroying viral phages and capsids using hydroxyl free radicals. Also, Taylor et al. [36], Chorus and Bartram [28], Yoo et al. [37] and Wickramamayake et al. [38] have all shown that low doses of peroxyl and nitroxyl ions (eqn. 6) are capable of destroying pathogens like *Mycobacterium avium, Cryptosporidium* and *Giardia lamblia.*

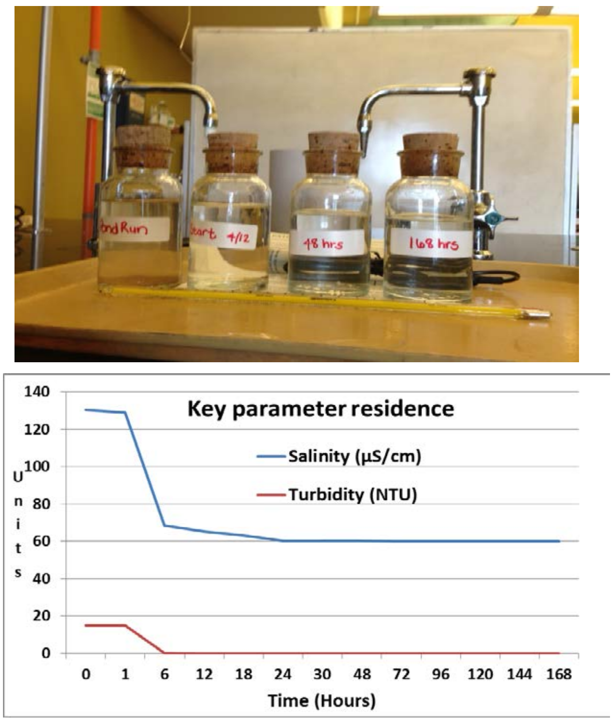

Figure 4 (a) PATHOGENA treated water samples over time (water gets cleaner from left to right); **(b)** Determination residence time (i.e. time it takes for PATHOGENA to purify untreated water).

NOTE: Acceptable limit for salinity is about 80.0 µS/cm and turbidity 0.0 NTU. Notice that PATHOGENA residence time is about 6 hours.

In view of the above, PATHOGENA water was subjected to bacteriological analysis using the EPA 'presence-absence' validation approach; Figure 5 presents the results**.** Figure 5a represents untreated bacterial colonies matched against its treated counterpart in Figure 5b. Notice that this study focused attention on total coliform (i.e. fecal coliform and E. *coli*) (Table 2); more detailed bacteriological analysis is planned for future studies. In the context of EPA drinking water quality standards, PATHOGENA appeared to destroy coliform bacteria very well; future studies will investigate other pathogens like *M. avium* and *G. lamblia*. To subject PATHOGENA to further validation, the results were matched against published data by the Vienna City Council on drinking water; the results are shown in Figure 6. Here again, PATHOGENA results compared favorably with Vienna City tap water (Figure 6b; $R = 0.99$; $p<0.011$; $N = 13$ [31]). Notice that the correlation between PATHOGENA and Vienna City water data was derived using basic spreadsheet capabilities of Microsoft Excel. First, a scatterplot was created between the two data sets after which the correlation equation and coefficient were derived.

The next question is how affordable PATHOGENA is to poor rural population? This question is not easy to answer unless full validation, quality control, technology component adjustments and licensing agreements are completed. The cost of the 100-gallon (*trash-can*) version of the PATHOGENA technology is about $1000.00, capable of delivering clean water daily to a rural African household of about 10 people all year round. That means, the cost of water per person over 365 days in a household is about $0.27. The above does not even count the life-span (minimum of 5 years) of PATHOGENA and the number of times it is can deliver clean potable water per day. Comparing PATHOGENA to conventional water investment in the developing world (estimated at $0.48/per person/day [39]), it is predicted that PATHOGENA could yield an economic return of nearly $7.00 per person per day, knowing that for every $1 invested in water and sanitation, there is an economic return of about $34.00 for many poor countries [40]. The above is further indication that PATHOGENA is a water purification technology with great promise.

Conclusion

The purpose of this study is to validate the PATHOGENA electron-activated reactor designed to treat contaminated water to make it potable. The goal is contribution to ongoing validation to help improve access to safe drinking water which is a major problem in many parts of the developing world. The validation process started with establishment of a water quality database created from analyzed contaminated water, EPA/West Virginia water quality standards and Vienna City Council (West Virginia) drinking water. The PATHOGENA water quality data showed remarkable improvements over contaminated sources, demonstrating water purification capabilities. When PATHOGENA was matched against previous data, the results (PATHOGENA) compared favorably both with EPA/West Virginia water quality standards and Vienna community drinking water (see Figure 6b; $R^2 = 0.99$; $p<0.011$; $N = 13$). It was also found that PATHOGENA is capable of delivering clean water at about $0.27 per person per day with an economic savings of nearly $7.00 at the same rate.

Future Studies

The current study has revealed PATHOGENA as a potentially reliable water purification system for supplying potable water in poor countries. However, there are a number of important questions still to be answered. For example, (1) how can we improve PATHOGENA's residence time (i.e. time for the system to treat contaminated water) using relatively inexpensive VIP generators? (2) Also, how do we determine PATHOGENA's ability to destroy some of the most harmful water-borne bacteria, e.g. *M. avium* Furthermore, (3) how can PATHOGENA ensure reliable power source (in poor countries) to continuously deliver safe potable water.

As noted above, an upgraded version of the VIP generator has now been designed, capable of reducing PATHOGENA's residence time from six to one hour. The next study will test this new generator and will report the results in a subsequent paper. Also, in the next study, more robust methods for bacteriological analyses, e.g. Betancourt et al. [25] and Kumar et al. [29] will be employed to fully isolate and characterize water-borne bacteria and other microbes. Finally, subsequent studies will investigate the potential of solar energy for powering the PATHOGENA system. Solar energy is viewed as a cheaper and more reliable source of power in tropical countries where continuous power supply is an important problem.

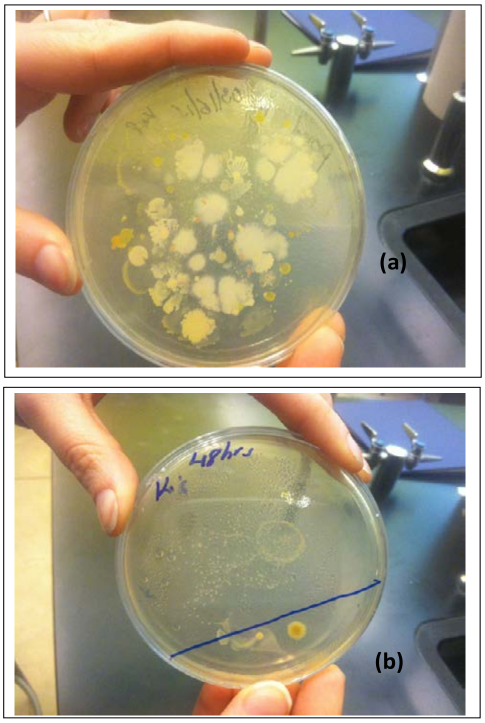

Figure 5: Determination of total coliform (including fecal and *E. coli*). (**a**) Untreated versus, (**b**) treated bacteria colonies.

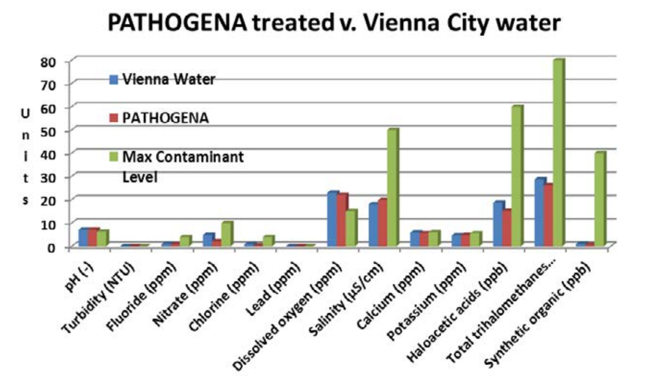

Figure 6: PATHOGENA-treated matched against Vienna city water.

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