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Validation of the EcH_2O Electron-Activated Reactor for Purifying Contaminated Water in Parkersburg (West Virginia)

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Abstract: This paper discusses validation of the EcH_2O portable *'batch-treatment'* electron-activated reactor field unit designed to purify contaminated water to make it safe and potable. The basic EcH_2O system consists of a 90-gallon plastic reactor tank (trash can), ionized nitrogen-oxygen (NI-OX^{TM}) vapor-ion plasma generator, and 1-micron electron separation (e^-SEP^{TM}) porous cartridge water filter. While the NI-OX^{TM} generator applies UV radiation to activate and split ambient air into aggressive water treatment agents in the form of free electrons and charged dissolved vapor ions, the e^-SEP™ cartridge is designed to absorb NI-OX™ treatment agents and solvated (free) electrons to induce filtration and rapid disinfection-kill of bacteria and other pathogens. The study started by creating a water quality database from contaminated surface water, EPA/West Virginia water quality standards, and Vienna City water. The EcH_2O purifier was run 14 days/month from April-September 2014 and samples analyzed for chemical and bacteriological quality. When the results were matched against published data, EcH_2O compared favorably with both EPA/West Virginia water quality standards and Vienna City water (R^2 = 0.99; p<0.011; N = 13). The EcH_2O purifier was found to be affordable and capable of delivering potable water to households in poor countries at about $0.27 per person per day with economic savings of nearly $7.00 at this rate.

Keywords: Validation, EcH_2O Reactor, Contaminated Water, Electro-Chemistry, EPA Water Quality Standards

1. Introduction

Nearly 800 million people representing 11% of the world's population have no access to safe drinking water; 40% of this number lives in Sub-Saharan Africa [1]. Consumption of heavy metals, organics/pesticides, and contaminated water leads to serious health and life longevity problems, and associated cultural and economic deprivation. Poor countries where guinea worm infection, typhoid fever, cholera, dysentery, hepatitis, gardiasis and parasitic blood diseases are prevalent suffer greatly. Health experts are also concerned about potential hazards posed by consuming contaminated water. Some water-related health hazards are described in Table 1. Furthermore, the search for water from long distances (sometimes 5 miles away from home) imposes health and economic burden on women and children who remain traditional 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 concerted research and capital investment in water supply should lead to 92% global 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]. Relative to wider treatment systems 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]. The electro-chemistry free-electron-activated water purification system (herein called EcH_2O technology) represents a meaningful paradigm shift toward a unique advanced H_2O treatment and purification approach. The scientific evaluation of one of the main domestic prototypes is the subject of this study.

The EcH_2O technology has proved successful at purifying highly contaminated water at some industrial facilities including the Denver Health Hospital, US Military and Navy facilities, and the MIT Nuclear Reactor Lab HVAC installation. Reports on the last two facilities have been reviewed in this study [14, 15]. The main purpose of this study is to validate the domestic (scaled-down) version of the EcH_2O system, for which we hypothesize the reactor's capability of purifying and delivering potable water at an affordable price to local people in poor countries.

Study Area

The inventor and patents-holder of the EcH_2O electron-activated reactor system is Dennis Johnson, CEO and President of EcH_2O International, LLC (Colorado). Through collaborative association with EcH_2O, this validation was implemented at the Ohio Valley University in West Virginia. 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 [16]. Surface and groundwater pollution is well-documented by authors like Kozar & McCoy [16], Tanner et al. [17], Foreman et al. [18], and Luttrell [19]. 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.

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

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
		Chlorine	Water additive used to control microbes; septic tanks	Eye and nose irritation; stomach discomfort
Organic Chemical Contaminants	Volatile	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
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

The parameters marked (*) were not studied because of lack of laboratory resources and will be addressed in the next study.

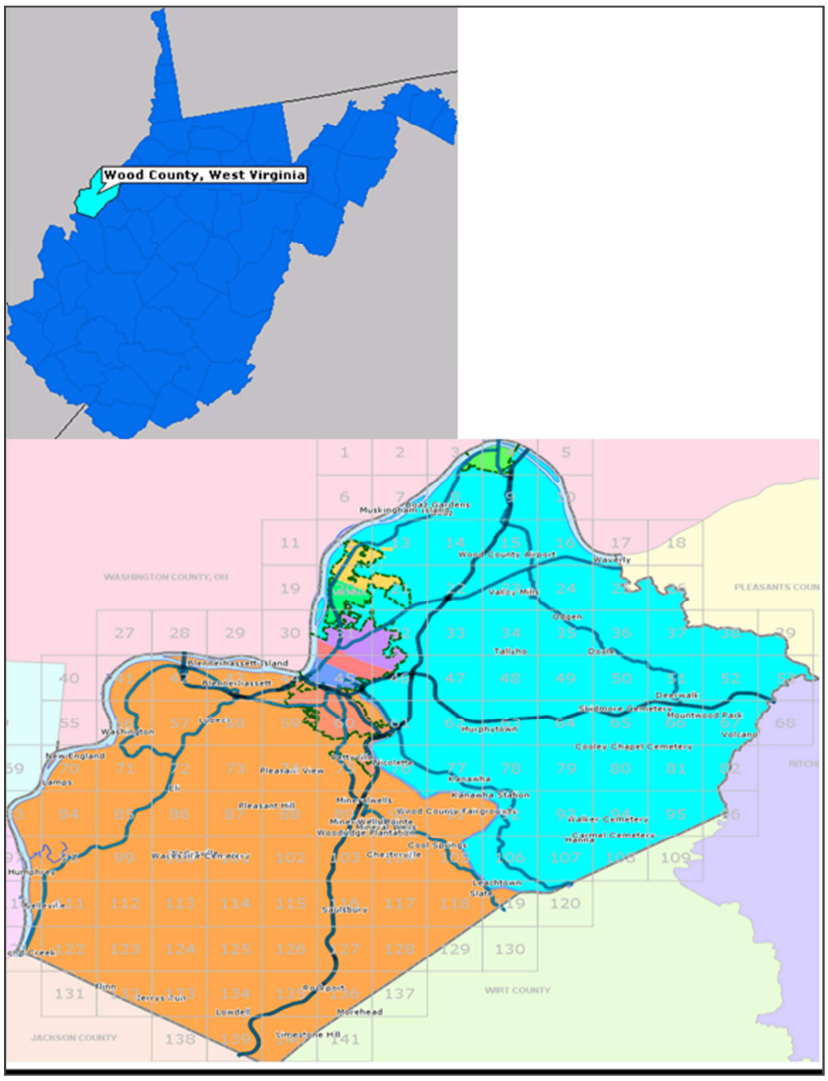

Figure 1. *(Top) Map of West Virginia showing Wood County study area. (Bottom) Map of Wood County; notice that the Ohio River runs downstream from the northwestern part serving as boundary between the States of West Virginia and Ohio. Contaminated water samples were collected from the Ohio River, Pond Run stream and Twin Lakes in grid 20 of the bottom map (Source: OnlineGIS.net, 2015).*

2. Materials & Methods

2.1. Materials

The domestic EcH_2O electron-activated reactor (Figure 2) is a 110-volts powered system and consists of: (1) 100-gallon plastic tank batch reactor (90-gallon treatment capacity); (2) ionized nitrogen-oxygen (NI-OX™) generator with a small fractional horse power delivery compressor; and (3) 1-micron electron separation (e^{-}SEP™) porous cellulose fiber water filter. The NI-OX™ generator unit and compressor are fastened to the tank cover while the filter is fitted about 10 inches above the inside base of the tank. The filter is connected to a fine bubble aeration diffuser using a ½" poly tubing (Figure 2). The principal component of the generator is UV radiation lamp (λ = 155nm) capable of splitting ambient gases (e.g. O_2 and N_2) into monoatomic charged particles using ultraviolet ionizing energy and magnetic emission. The filter is a high quality polarized media designed to eliminate bacteria and remove descaled and coagulated solids and debris.

2.2. Methods

There are multiple ways of performing industrial and technology process validation tasks, some of which are critically reviewed by Vandervivere et al. [20]. In this case, a modified version of the US Food and Drugs Administration (FDA) approach was adopted [20]. The key point of the FDA guidelines titled *"General Principles of Validation"* and summarized by Long et al. [21] is that technology process validation should involve: (1) multiple test runs; (2) analysis of test runs; and (3) statistical correlation with standardized process or globally tested products. If we consider for instance, a brand new pharmaceutical product, successful runs of three consecutive product batches against a standard or well-known product is viewed as a validated process.

Against this background, results from the EcH_2O reactor were analyzed qualitatively and quantitatively and matched against published water quality standards.

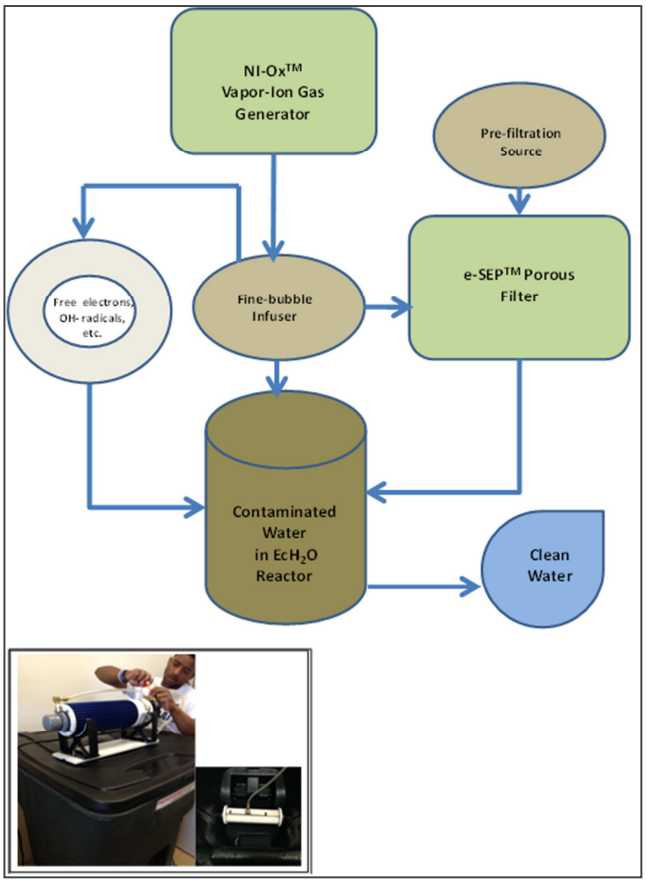

Figure 2. *Schematic of the EcH_2O electron reactor. The inset (below) shows the NI-OX™/VIP generator on top of the reactor tank and e-SEP™ filter at the base of the tank.*

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-September, each in 2013 and 2014. The Vernier LoggerPro-3 analytical procedures were used for chemical analysis and results matched against World Health Organization (WHO), US Environmental Protection Agency (US/EPA) and West Virginia water quality standards [22-24] (Table 2). The US/EPA method for determining organic compounds in drinking water was also applied [25, 26]. Here, 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 [25, 27-30]. 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 further verified using Macrady's probability tables and the US/EPA bacterial presence/absence approach [25, 31, 32].

Next, the EcH_2O 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 EcH_2O's efficiency in terms of water treatment duration (i.e. residence time), and also to optimize water sampling times. The EcH_2O results (Table 2 & Figure 3) were matched against archived and published data [24, 31, 32, 33].

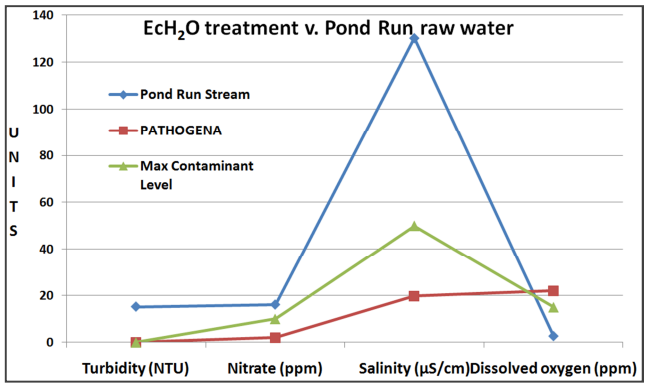

Figure 3. *EcH_2O electron-treatment matched against untreated water (Pond Run stream) and verified using EPA water quality data (Maximum contaminant level).*

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

The detailed process chemistry of the EcH_2O technology is described by Dennis [34]. A summarized version is presented here:

1) 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.

$$O_2 \frac{UV}{MagE} \rightarrow O^{\alpha+} = O^{\alpha-} \frac{UV}{MagE_{O_2^-}} \rightarrow O_2^-, O_2^{2-} \leftrightarrow O^0 - O^0 - \quad (1)$$

(singlet oxygen)

2) 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 accelerate oxygen ionization.

$$N_2 \frac{UV}{MagE} N^{\alpha+} - N^{\alpha-} \frac{e^-}{O_2 ionized} \quad (2)$$

(free electron [e^-] plus accelerating ionized O_2)

3) 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 (Equation 1).

$$O_2 \frac{UV}{MagE} O_3 \frac{UV}{MagE} \rightarrow O_3^+ \leftrightarrow O_3^- \frac{UV}{MagE} \rightarrow O_2^- \quad (3)$$

(superoxide ion)

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

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

5) 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.

$$xO_2^- + H_2O \frac{e^-}{stream} \rightarrow xH_2O_2 \leftrightarrow xOH^- + xOH_2^-(scavenger) \quad (5)$$

$$O_2^- + H_2O \frac{e^-}{MagE_{\Delta T}} \rightarrow H_2O_2 \quad (6)$$

6) Generation of trioxidane stream vapor: Thermal reaction of hydrogen peroxide and ozone reacts can release free electrons, and potential production of trioxidane (Equation 7), superoxide ions and peroxone (Equation 8). 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.

$$H_2O_2 + O_3 \frac{e^-}{MagE_{\Delta T}} \rightarrow H_2O_3 + O_2^- \quad (7)$$

$$O_3 + H_2O_2 \frac{e^-}{\Delta T} \rightarrow H_2O_5 \quad (8)$$

$$N_2^+ + 3O_2^- + 2H_2O \frac{e^-}{MagE_{\Delta T}} {}^-O_2 - N_2^+ - O_2^- + 4OH^- \quad (9)$$

Table 2. *Quality of Parkersburg water sources matched against EPA standards.*

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	Absent

*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.

3. Results & Discussion

Table 2 summarizes contaminated water data archived for summer of 2013 and 2014. The turbidity, nitrate and salinity data particularly confirm previous reports that raw water pollution is a problem in the study area [16-19]. 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 EcH_2O reactor for decontaminating impure water and how long can the system deliver clean potable water? Also, (2) how affordable is the EcH_2O technology for adoption by poor communities in the developing world? As stated above, results from EcH_2O treated water were first matched against untreated samples and verified using EPA drinking water standards. Figure 3 presents the results. The data in Figure 3 show how well EcH_2O decontaminates raw water and closely satisfies EPA standards. It is worth noting how the EcH_2O purifier decontaminates raw water when parameters like turbidity and salinity are considered (see Figure 4b). To determine water treatment cycles and duration, water samples were drawn and tested after one hour, and every six hours thereafter for 168 hours (i.e. 28 tests per week). The time intervals were chosen randomly using expert knowledge. A summary of the results is presented in Figure 4. Notice that water treatment after the

first hour did not produce clean water. However, good quality water was produced after six hours (Figure 4). The next study will test an improved (more powerful) version of NI-OX™ vapor-ion plasma generator to help reduce the EcH_2O's residence (treatment) time to about 1 hour. Also, field validation in a developing country will help to confirm current results. Plans are being made to achieve this.

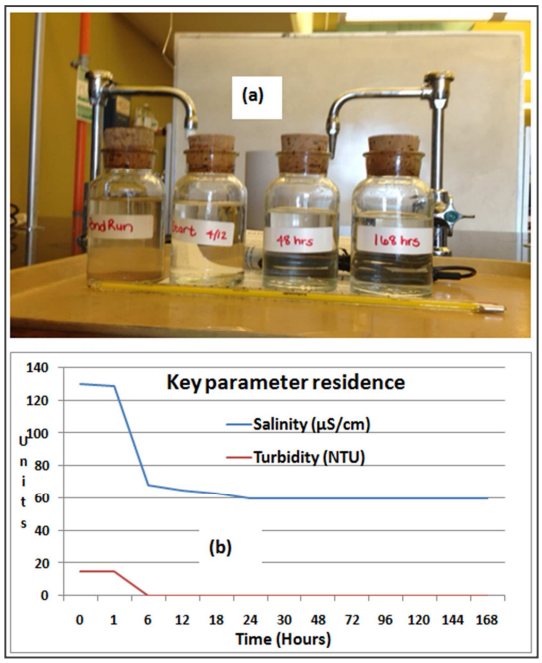

Figure 4. *(a) EcH_2O treated water samples over time (water gets cleaner from left to right); (b) Determination residence time (i.e. time it takes for EcH_2O to purify untreated water).*

NOTE: Acceptable limit for salinity is about 80.0µS/cm and turbidity 0.0 NTU. Notice that EcH_2O residence time is about 6 hours.

An important question is microbiological quality of EcH_2O treated water. Previous studies by Pham Thuy et al. [35], Langlais et al. [36], Wolfe et al. [37], and Taylor et al. [38] have reported microbial inactivation from electron-bombardment, free radical attack, and ozone and peroxone toxicity. Peroxone is a mixture between ozone and hydrogen peroxide (Equation 5). The theoretical basis of this method is that heavy oxidizing agents like peroxides, trioxidanes and peroxones (Equations 5-8) are capable of breaking down functional proteins of microorganisms through attack on cytoplasmic membranes [32, 36-38]. Wolfe et al. [37] for example, have reported the destruction of viral phages and capsids using hydroxyl free radicals. Also, Chorus & Bartram [30], Taylor et al. [38], Yoo et al. [39] and Wickramamayake et al. [40] have shown that low doses of peroxyl and nitroxyl ions (Equations 5, 6, 9) are capable of destroying pathogens like *Mycobacterium avium, Cryptosporidium* and *Giardia lamblia.*

In view of the above, EcH_2O water was subjected to bacteriological analysis using the methods described earlier on [25, 27, 30-32]. Figure 5 presents the results**.** Figure 5a represents untreated bacterial colonies matched against its treated counterpart in Figure 5b. It is important to emphasize that our initial studies focused attention mainly 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, EcH_2O appeared to destroy coliform bacteria very well. Future studies will investigate other pathogens like *M. avium* and *G. lamblia*. To subject EcH_2O to further validation, the results were matched against data archived by the Vienna City Council on drinking water; the results are shown in Figure 6. Here again, the EcH_2O results compared favorably with Vienna City tap water (Figure 6b; R^2 = 0.99; p<0.011; N = 13 [33]). The correlation method was established using a scatterplot between the EcH_2O and Vienna City water data (13 maximum data points). A linear best-fit equation was first derived to determine the correlation coefficient (R^2).

The next question is: how affordable is EcH_2O to poor rural populations? This question is not easy to answer unless full validation, quality control, technology component adjustments and licensing agreements are completed. However, the cost of the EcH_2O '*trash-can*' water treatment system is estimated at $1000.00. It is predicted that on a daily basis, the above prototype will deliver clean water to a poor African household of about 10 people all year round. That means the cost of water per person over 365 days (per household) is about $0.27 per day. This does not even consider the life-span (minimum of 5 years) of the EcH_2O purifier and the number of times it can deliver safe potable water per day. Comparing EcH_2O to conventional water investment in the developing world (estimated at $0.48/per person/day [41]), it is predicted that EcH_2O will 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 [41]. Notice that the above is only a crude economic prediction based on the following calculation: [($0.48-0.27)/$1.00*$34.00].

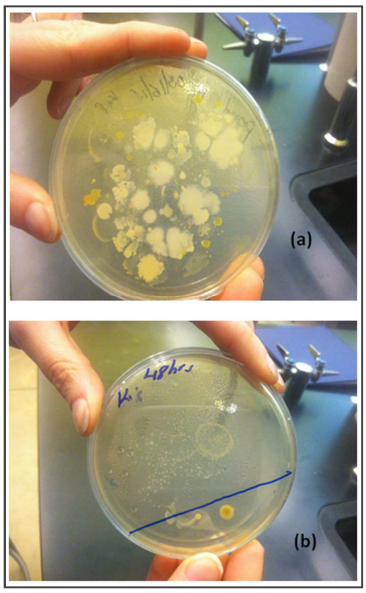

Figure 5. *Determination of total coliform (including fecal and E. coli). (a) Untreated versus, (b) treated bacteria colonies.*

The above assumptions coupled with the water quality results show the EcH_2O *'trash-can'* reactor as a simple water purification technology with great promise. Future studies will investigate ways to make the technology more accessible and affordable.

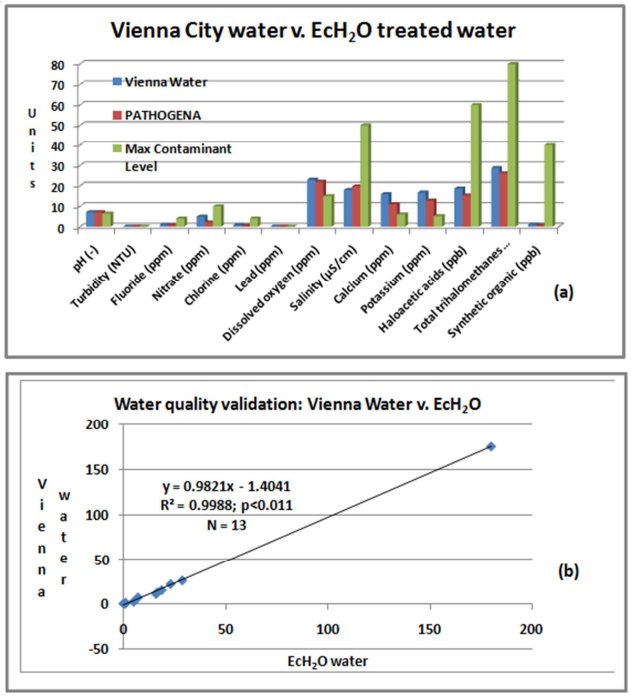

Figure 6. *EcH_2O-treated matched against Vienna City water. Notice the close resemblance of Vienna versus EcH_2O water - (b) represents statistical interpretation of the data displayed in (a).*

4. Conclusions

This paper has discussed validation of the EcH_2O electron-activated reactor designed to treat contaminated water to make it potable for poor countries where safe drinking water is a major problem. The validation process started with establishment of a water quality database created from analyzed contaminated water, EPA water quality standards and Vienna City water. The EcH_2O treated water showed remarkable improvements over contaminated sources, demonstrating strong water purification capabilities. When EcH_2O results were matched against previous data (i.e. EPA water quality standards and Vienna City water), it (EcH_2O) compared favorably well (R^2 = 0.99; p<0.011; N = 13) with standard sources as shown in Figure 6. EcH_2O was found capable of delivering clean water to poor households at about $0.27 per person per day with an economic savings of nearly $7.00 at this rate.

5. Future Studies

The current study has revealed EcH_2O 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 EcH_2O's residence time (i.e. time for the system to treat contaminated water) using relatively inexpensive NI-OX^{TM} vapor-ion plasma (VIP) generators? (2) Also, how do we determine EcH_2O's ability to destroy some of the most harmful water-borne bacteria, e.g. *M. avium*? Still, how can we ensure EcH_2O's ability to decontaminate hazardous chemicals like arsenic, mercury and lead? Furthermore, (3) how can EcH_2O ensure reliable power source (in poor countries) to continuously deliver safe potable water?

As noted above, an upgraded version of the NI-OX^{TM} VIP generator has now been designed to potentially reduce EcH_2O'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. [26] and Kumar et al. [30] will be employed to fully isolate and characterize water-borne bacteria and other microbes. Finally, future studies will investigate the potential of solar energy for powering the EcH_2O system. Solar energy is viewed as a cheaper and more reliable source of power in developing countries where continuous power supply is an important problem.

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