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Utilisation of Solar Energy Driven Photochemical Processes for River Water Purification

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Abstract: *More than two billion people across the world do not have access to potable water. Communities globally are struggling with epidemic level disease outbreaks, limited water supply among other large-scale public health risks. Water is essential for life and several regions across the world have poor infrastructure for the management of potable water resources and lack critical wastewater treatment facilities. As the population of the Earth grows rampantly, the demand for water resources is increasing exponentially. Large-scale critical infrastructure chains are required to produce potable water from raw water sources, and developing countries continue to struggle economically and cannot afford the same treatment chains as the developed world. This research project evaluated the feasibility of two photocatalytic / photo-Fenton solar reactors on their capabilities to breakdown water contaminants present in natural hydro-systems and freshwater resources namely rivers in Chatham, Kent, England between September 2015 and August 2017. The photo-Fenton reaction and solar-photochemical reactors were designed, constructed, and tested for the removal efficiencies of Chemical Oxygen Demand (COD), ammonia, nitrates, nitrites, and phosphates via LCK curvetted tests, in addition to turbidity and colour. The water quality analysis and results showed that oversaturation of the photo-Fenton reagents reduces the effectiveness of the reaction, and that finding the correct chemical balance has a greater impact on the removal efficiencies of the five pollutants than the use of ultraviolet (UV) light catalyst. Under the conditions set by this research project, a smaller diameter of piping yields the best removal efficiencies of pollutants. The optimal photochemical balance of H_2O_2: Fe^{2+} has more of an impact on the effectiveness of treatment than the use of UV radiation. The ideal H_2O_2: Fe^{2+} ratio for the treatment of river water is close to 100:1 mg/L. The impact of semi-variables such as diameter of pipe and UV influx on the effectiveness of treatment are not noticeable compared to the effect of changing the photo-Fenton chemical ratio. Moreover, the photo-Fenton process' removal efficiency is directly proportional to the remaining H_2O_2 concentration, as the photochemical reaction proceeds.*

Keywords: *Photo-Fenton, Heterogeneous Fenton, Photochemical treatment, Solar Energy, River Water, Detoxification, Drinking water, Solar radiation*

1. Introduction

Around 2 billion people around the world do not have access to clean and safe drinking water, and approximately 3.6 billion people – 46% of the world's population – lack adequate sanitation services, according to a new United Nations World Water Development Report (UNESCO, 2023). As the population of the Earth grows exponentially, the demand for water increases. Large infrastructure chains are required to produce potable water from raw sources and developing countries that struggle economically cannot afford the same treatment chains as in the developed world. Across the United Kingdom (UK), wastewater and stormwater network systems are often linked to the same sewers and hence go through the same treatment process (DEFRA, 2012).

The water and wastewater treatment works chain implemented in the United Kingdom (UK) are typically a four-stage process: preliminary, primary, secondary, and tertiary (DEFRA, 2012). Each stage involves various infrastructure in place to treat the wastewater. Preliminary screening involves removing the insoluble solids in the wastewater through filtering machines. Primary treatment use sediment basins that settle the wastewater (DEFRA, 2012; Riffat, 2012). This has compound utility in that sludge (liquid waste) settles at the bottom of the basin where it is pumped out to a treatment facility while fats and oils rise to the surface due to the differing densities where a skimmer removes and segregates the oils for use as glycerides in processes like saponification. The secondary process specifically focuses on decreasing the biological content of the wastewater, generally by aeration and the addition of a controlled "good" bacteria that

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consumes the pathogens in water, converting it into carbon dioxide (CO_2), water, and energy for the "good" bacteria's own reproduction (Sarkar et al., 2014; Putatunda et al., 2019). The tertiary stage involves processes that are energy intensive, and often involve the addition of oxidising chemicals to disinfect the water of microorganisms. According to the World Bank Group (2012), 99% of all impurities in water are removed by tertiary stage processes.

The St Mary's Island development in Chatham, Kent, England, the UK began development in the late 1990s, built on an island in the River Medway and entered additional phases of renovation into a small village that are still ongoing (SMIRA, 2015). Currently there are more than 2000 domestic homes and dwellings on the edge of River Medway. The initial research ideas of the project were developing a concept of a hypothetical water treatment facility for the existing St Mary's Island development, drawing water resources from the River Medway to produce potable water. A full-scale water treatment plant would not be feasible to construct, although the river water quality would not require extensive treatment processes and infrastructure. Upon further independent research it was discovered that the team of hydrologists had already designed the intended storm water drainage systems for the new development but had not considered the prospect of drawing water from the River Medway, treating it to drinking standard in an underground laboratory and distributing the potable water around the island. This would save energy, expense, and encourage recycling of water, albeit on a small scale.

River water and wastewater are not of the same quality. This is primarily down to the pre-treatment of river water from wastewater treatment plants (WWTPs) to reduce the pollutants in the water to specific standards of quality before being allowed to run into the channel. Even with the pre-treatment, river water is not fit for human consumption, though. Producing potable water from a municipal source can be very expensive and may not be the ideal option for a developing country to implement. Considering that the pollutant levels of river water are already lower than that of a municipal source, it would therefore cost less to treat river water to drinking standards than it would to treat municipal water. Since approximately 90-99% of all impurities in water are removed by tertiary stage processes (Malato Rodríguez et al., 2004; World Bank Group, 2012), an efficient tertiary treatment process alone may be enough to bring the physical, chemical, and biochemical parameters up to drinkable standards. Interest was taken for the Solar driven photo-Fenton reaction and treatment process. This paper reports the project work that was to build and test two photo-Fenton reactors, compare their pollutant removal efficiencies, and deduce whether the St Mary's Island housing development would benefit from implementing a similar reactor to produce potable water in the UK.

2. Background of Round of Solar Photochemical Reactions for Water and Wastewater Treatment

Solar disinfection (SODIS) in its most primitive state was a concept developed from the need for effective water treatment techniques that could be used in areas of the world where drinking water is not readily accessible. World Health Organisation (WHO) documented the efficiency of four methods of water sanitisation to combat the health issue of diarrhoea in developing countries (Clasen and Haller, 2008; WHO, 2009). Two of those methods being chlorination and solar disinfection (Cho et al., 2003; Chatzisymeon et al., 2011). The chlorination method required the use of sodium hypochlorite chemical which is an ionic compound that allows the dissociation of Chloride (Cl^-)ions into water and the solar disinfection method simply involved containing raw water in a see-through bag and leaving it out in the sun for 6 or more hours. The study revealed that solar disinfection is only marginally outperformed by chlorination in terms of its ability to disinfect, although it does not rely on distribution of chemicals, which is an advantage over chlorination.

Ultraviolet (UV) radiation from the sun is scattered by the stratosphere of planet Earth, as the wavelengths of this kind of radiation lie within the ultraviolet range (280-400nm). More specifically, UV radiation is characterised into three categories based on wavelength range; UV-A (315-400nm), UV-B (280-315nm) and UV-C (<280nm) (Cho et al., 2003; Chatzisymeon et al., 2011). These different categories of radiation have different properties, and as such, have different effects on organic matter. All organic matter absorbs light wavelengths; although individual molecules may be able to absorb wavelengths and reflect others, which is what give molecules their colour. This chemical group in a molecule is called a chromophore and this in turn makes UV radiation dangerous as all molecules have an innate ability to absorb the high energy, short wavelengths of the UV radiation directly. Once absorbed, the UV wavelengths react with the organic molecules through photodynamic reactions (Ito, 1983).

Proteins present in waterborne microbes are especially sensitive to UV radiation, and proteins within these microbes form the four bases for Deoxyribonucleic acid (DNA). The absorption of UV light in DNA causes adjacent C and T bases to start reacting with each other rather than with their complimentary A and G bases. This irregular pairing pattern causes the shape of DNA to change from the standard double-helix in affected areas. In turn, this brings complications with copying DNA and inhibits the production of bases in those affected areas (McGuigan et al., 2012).

The effects of DNA manipulation are inhibited growth and reproduction, and as such, inhibiting the ability of pathogens and microbiological pollutants alike to multiply renders them inactive. Although wavelengths in the UV-A spectrum are not sufficiently energised to be able to directly affect DNA bases, the absorption of UV-A produces free radicals or oxygen singlets that can damage components of a cell through oxidation (Sinha and Häder, 2002). Wavelengths in the UV-B and UV-C range can affect DNA bases although they are easily absorbed by the atmosphere. The stratosphere allows only a small dose of UV-B to reach ground level and almost totally absorbs UV-C.

The effects of UV radiation damage on DNA are not necessarily permanent, and there are various DNA repair mechanisms that reconfigure DNA over time oxidation (Sinha and Häder, 2002). Consequently, methods of UV disinfection must be tested to find how efficient the method of UV disinfection is at inhibiting not only the inactivation rate, but also how effective the treatment was at disabling the regeneration of tested pathogens over a period. Cho et al. (2003) and Chatzisymeon et al. (2011) reported in depth on the survival rate of *Escherichia coli* (E. Coli) under various conditions such as different UV wavelengths, photocatalysts and different types of water.

The foundations of photochemical and photocatalytic reactions stem from Henry J. Fenton's discovery in 1894 that reported hydrogen peroxide could be activated by Iron (II) salts to oxidise tartaric acid (Fenton,1894). This became pivotal work for Haber and Weiss in 1934 to discover the Hydroxyl radical (•OH). It was then realised that the (Hydroxyl radical-•OH), high electronegativity makes it a potent oxidising agent for water and wastewater treatment. From then, plentiful research has been conducted, and within the last few decades understanding the impact of oxidising agents on various organic molecules has improved in a variety of different environmental cases.

Researchers (such as Balzani and Carassiti (1988) and Šima and Makáňová (1997) assessed the effects of UV radiation in the form of visible light on the Fenton reaction and developed the mechanism for the Photo-Fenton reactions. These studies revealed that the photochemical processes of Iron (III) have favourable properties for producing more hydroxyl radical (-•OH) and oxidised ligands (Balzani and Carassiti, 1988); Šima and Makáňová, 1997). The processes consequently create more reaction paths with the organic target pollutant, ultimately resulting in faster reaction times and further degradation of said target pollutant when compared to the original Fenton reactions (known today as the thermal Fenton reactions).

In 1990, Fenton's original discoveries of the interaction of hydrogen peroxide and iron (II) were reviewed, and the Fenton reaction was developed in laboratories on the small scale. It was documented that the Fenton reaction has a slightly faster reaction time in the presence of visible light, and so the Fenton reaction was then split into the thermal Fenton reaction and the Photo-Fenton reaction, that are both linked by similar free radical mechanisms although the photo-Fenton reaction utilises light as a catalyst. Pignatello et al. (2006) assessed the photochemical mechanisms for various forms of the Fenton reactions. This development complimented the aims of solar disinfection through UV light well, and more recent studies have attempted to combine the applications of photo-Fenton reactions and UV disinfection to treat both water and wastewater. Equations 1-3 adapted from Wayne, (1988) and Pignatello et al. (2006) shows the photochemical processes involved:

$$Fe^{2+}(aq) + H_2O_2 \rightarrow Fe^{3+}(aq) + \bullet\, OH + OH^- \qquad \text{Eq.1}$$

$$Fe^{3+} + HO^- \rightarrow FeOH^{2+} \qquad \text{Eq 2}$$

$$FeOH^{2+} + H_2O_2 -^{hv}\rightarrow Fe^{2+} + \bullet\, OH \qquad \text{Eq.3}$$

As such, this study provoked further research into processes that augment the solar disinfection reaction to increase its viability. Examples include semiconductor photocatalysts and photosensitisers.

3. Experiment Details / Methodology

The three mainly documented reactor designs are non-concentrating, medium-concentrating and high-concentrating reactors. Non-concentrating reactors are typically designed without an emphasis on redirecting the light that enters the solar collector, whilst the medium and high categories are generally dictated by the temperature range that the reactor reaches under the concentration of sunlight (150-400˚C for medium and over 400˚C for high), as described by Tota-Maharaj and Meeroff (2013).

3.1. The Design and Fabrication for the Solar Photoreactors

Strips of aluminium film were applied to a plywood base. Thereafter, Borosilicate glass tubing with 32mm and 44mm diameter alongside flexible tubing were used to connect the solar-photoreactor together, alongside aluminium reflective surfaces. Silicone was used to seal various ends and connectors of the glass tubing to ensure no leaks occurred. Plastic clips and horseshoe clamps were placed at the end sections of the glass tubes and slides along the edges of the photoreactor to stabilise the U-bends. Two Pipestock Ltd. (Romsey, England, the UK) digital flow meters with a range of 1-40 litres per minute were placed at the entry and exit points of the solar reactors. Using the design from Figures 1 (a) and (b) a materials list was created to begin procurement of the materials. Figure 2 (a) and (b) display the 44mm Diameter reactor and the 32mm Diameter reactor, referenced as Solar Reactors and 1 and 2, respectively. The materials list for both reactors are in Table 1.

3.2 The Photo-Fenton Reaction

The photo-Fenton reaction involves the use of highly oxidising chemicals that are sensitive to light, and balance of the reaction requires precision in the volume of reagents allowed to mix. Since the sensitivity to light only takes effect once the photo-Fenton reactants are mixed and added to the raw water supply, the pre-test phase (which involves a few processes in the water and environmental engineering laboratory to make the water

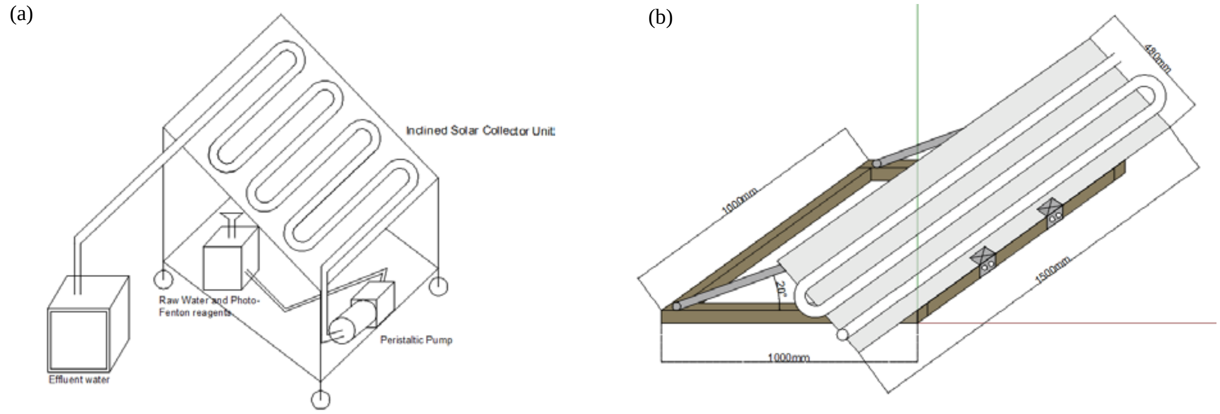

Figure 1. (a) Isometric Serpentine Array of Solar Photoreactor (b) Schematic of the Solar Photochemical Reactor Designs
Source: Adapted from Tota-Maharaj and Scholz (2013) and Tota-Maharaj and Paul (2015)

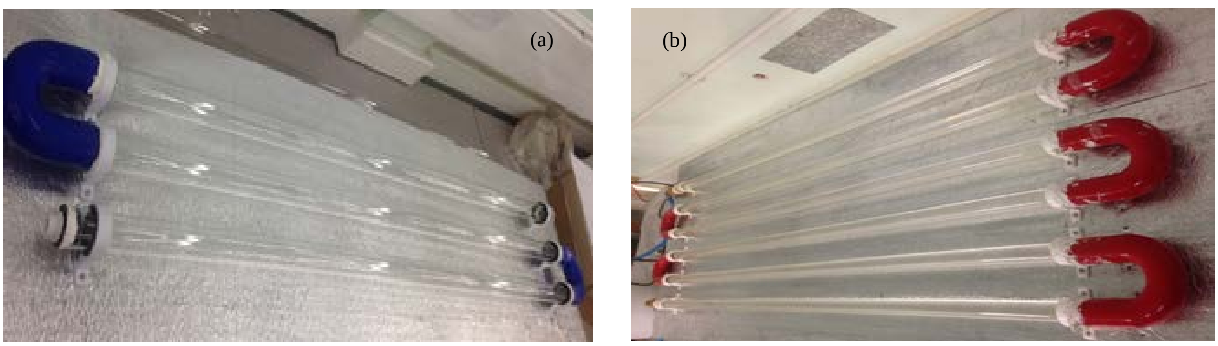

Figure 2. (a) 44mm Diameter reactor, referenced as Solar Reactor 1; (b) 32mm Diameter reactor, referenced as Solar Reactor 2

Table 1. Materials List for Solar Photochemical Reactors

Function	Materials	Specifications
Effluent water container	Steel container	Inert, volume capacity between 40-60L
Raw water container	Steel container	Inert, volume capacity between 40-60L
Water distribution through pipe network	Peristaltic pump	1-40Litres/hour flow rate
Reflective surface	Aluminium sheet	Low malleability, highly reflective of UV-A radiation, 1.7m width 0.5m height
Piping – main reactor frame	Straight borosilicate tubing	44mmm diameter, 1.6mm wall thickness, 4.05m required
Piping – adjoining pieces to link reactor chamber lengths	U-shaped bends	Inert material, 44mm diameter, compact, transparent- Solar Reactor 1 Inert material, 32mm diameter, compact, transparent- Solar Reactor 2
Piping – flexible tubing connecting all apparatus together	Flexible inert tubing, exact material not yet found	Must be able to fit onto varying diameters, opaque is fine, ability to withstand water pressure, corrosion resistant
Insulation from light	Fibreglass	Easily attached to materials
Photo-Fenton reagents	Chemicals	N/A
Apparatus stand	Steel trolley	Attached castor wheels to allow for mobility
UV-A wavelength	Low pressure mercury UV lamp (315-400nm)	Quantifiable UV-A dosage

testable) does not have the complication of being light sensitive.

Essentially, the raw river water was split into two separate containers, one had the required Fe (II) concentration and the other had the required H_2O_2 concentration. This separation was to prevent the reaction occurring before entering the reactor. There is the issue of chemical balance for the photo-Fenton reaction. If the concentration of photo-Fenton reagents used was too high, it would lead to rapid oxidisation of the Fe (II) to form iron (II) hydroxide or iron (III) hydroxide which are both turbid solutions. This would spoil not only the data received, but it could also potentially stain and ruin the apparatus. The concentrations of Fenton reagents needed is based on the quality and volume of the raw water being treated.

Careful research and appropriate testing of the raw water once collected is the way to ensure the chemicals are correctly mixed. In terms of achieving the accuracy of reagents being added to solution, it is possible to use laboratory processes such as titrations to achieve molar accuracy.

3.3 River Water Collection and Sample Preparation

River water was collected twice weekly from the River Medway Kent, to begin the pre-testing phase of the water quality. Once the river water was collected, it had to be treated chemically prior to being used in the reactors. The reason for this was to add the photo-Fenton reagents and to bring the river water to an appropriate pH to facilitate the photo-Fenton reaction. Based on previous study, the photo-Fenton reaction has the highest inactivation rate of bacteria with a pH between 3 and 3.5 (Bechtel Corporation,1991). Previous studies also reveal that the correct proportions of Fe^{2+} and H_2O_2 must be found depending on how polluted the water sample being tested is. With insufficient H_2O_2, Fe^{3+} may precipitate and stain the apparatus, as well as pollute the samples. Similarly, too high quantities of H_2O_2 and Fe^{2+} will cause a heavy oxidation reaction and cause the water sample to become far too turbid and polluted to be tested.

The pre-test phase in the links laboratory involved experimentation with the collected river water to find three ideal concentrations of Fe^{2+} and H_2O_2 as well as to acidify the water to a pH of between 3 and 3.5] (Salgado, et al., 2013). Previous study conducted by Rabelo et al., (2014) showed that the ideal ratio of reactants for a Kraft Pulp Mill was 500mg/l of H_2O_2 to 50mg/l of Fe^{2+}. Although in a general case, a ratio of 100:1 yields the greatest efficiency of Chemical Oxygen Demand (COD) removal. This is because the concentration of H_2O_2 in a Fenton reaction gradually decreases over time, contrasted with a sharp decrease within the first 30 minutes of concentrations less than 100:1. With a proportion of 100:1, the H_2O_2 is homogenous enough within the solution to last the entire reaction length, decreasing in a more linear fashion, rather than a steep decrease and plateau. As such, samples were prepared with the ratios of 100:1, 10:1 and 2:1, so that concentration can become another variable to test, with the expected trend of efficiency to go from high proportions to low.

3.3.1 Experimental Methods for Testing Proportions of Photo-Fenton Reagents

After the volume of river water was selected, the pH was measured and adjusted to 3-3.5 using the addition of sulphuric acid. The molecular weight of $FeSO_4.7H_2O$ was calculated and the desired proportion measured with the selected volumetric loading of river water. The calculated molecular weight of H_2O_2 was needed to establish the desired proportion by using chosen volume of water. A zero weight of the weighing dish was set prior to any photochemical additions; the acidified river water was placed in a beaker and onto a metallic stirrer and a measured mass of Fe^{2+}, followed by H_2O_2.

This procedure was carried out multiple times to observe the results of the reactions over time. The first experiment involved measuring out quantities for a proportion of 2000mg/l and 200mg/l of H_2O_2 and Fe^{2+} respectively (a 10:1 ratio). These experiments in the environmental engineering laboratory were using river water from the first sample of water collection, and so small quantities of water were used to preserve as much of the water as possible for the actual laboratory testing. 400ml of water was measured out approximately by using a volumetric beaker. The pH was then adjusted by adding 1.25mol sulphuric acid to the sample to raise the pH to between 3 and 3.5.

3.3.2 Water Quality Analysis

Water quality sample tests were carried out for ammonia, nitrites, nitrates, phosphates, and COD. Using a continuous process means extracting the river water from each reactor at regular time intervals during the test. Before the test began, 100ml of each chemically pre-treated river water sample was mixed and the LCK water quality sample tests were run for time = 0s. From there, samples were taken every 15 minutes up to 1 hour, with the LCK tests being conducted in the time spaces between samplings. Previous studies suggest that the reaction peaks at approximately time (t) = 30 mins and from that point, the reaction begins to follow a predictive trend. As such, it was not required to conduct the experiment for times above one hour, as the trend will most likely be very similar from 30 minutes onward and will also give a good extrapolation of how the trend behaves above 1 hour.

3.4 The Chick-Watson Disinfection Model

Experimental data from tests undertaken in the past have been used to develop mathematical models to predict the bacterial survival result of water disinfection, and one simple model is the Chick-Watson model, as shown in Equation 4 and in the report by Cho et al. (2003) and Chatzisymeon et al. (2011). This model is acceptable for use in this project since flow is assumed to be uniform. The Chick-Watson first order differential equation expresses both microorganism and inorganic inactivation rates. Corrections to the Chick-Watson model take more considerations for the test environment into account. The Chick-Watson model gives us a value for the bacterial survival rate, quantifying the effectiveness of disinfection in the form of a ratio.

$$\ln \frac{N}{N_0} = -kiT \rightarrow \frac{N}{N_0} = e^{-kiT} \qquad \text{Eq.4}$$

where N is the bacterial density after exposure in colony forming units (CFU), N_0 is the initial bacterial density exposure (CFU/ml), N/N_0 is the bacterial survival ratio, k is the inactivation rate constant (cm^2/µWatt-min), i is the intensity of incoming UV-A radiation (µWatt/cm^2), and T is residence time (minutes). The residence time is the time taken for influent water to pass through the reactor, and as such can be quantified by equation:

$$T\ (Residence\ Reactor\ Time) = \frac{V}{Q} \quad \text{Eq.5}$$

The Resident Time in the reactor (T) is calculated with V, the total volume of the reactor, and Q, the flow rate of water passing through the reactor (litres/minute). The use of the Chick-Watson equation has a few requirements involved. Firstly, the need to prepare bacteria cultures in petri dishes enabling a count of N_0 and N. Secondly is the need for a peristaltic pump to set a flow rate and determine the residence time, T.

4. Results and Discussion

Blank sampling testing compared the pollutant levels over time in distilled water, river water and finally pre-treated water occurred in this study. This gave a good benchmark trendline for the water pollutant values, and results showed the effect of both solar reactors. The photochemical treatment mechanisms and remediation of the river water samples, in addition to the length of time photochemical treatment was needed to reach the approach water quality standards to that of clean potable water. The general trends of the curves presented in Figures 3 (a)-(d) illustrate that the concentration of river water pollutants is decreasing with time, indicating that the photochemical reaction is occurring at a relatively good rate. The performance of Solar Photoreactor 1 versus Solar Photoreactor 2 is presented in Figures 3 with respect to effluent concentrations of nitrites, nitrates, phosphates, and COD.

The experimental performance of Solar Photoreactor 1 demonstrated a higher kinetic reaction rate when compared with that of reactor 2, with both, however, being effective at reducing the water pollutant concentrations. The steeper gradients demonstrated a faster remediation or disintegration reaction time. There were no significant differences or drastic occurrences between the Chick-Watson disinfection model curves for the measured inflow and outflow concentrations, with a few minor anomalies with extremely low concentrations of nitrites and nitrates. The fact that these pilot-scaled experiments provided similar curve shapes for the two photoreactors suggests that the photo-Fenton reaction is occurring successfully in both experiments and confirms the reliability of the results. The data measured and generated from this study showed the efficacy of the Solar energy driven Photo-Fenton Processes and can be used when comparing the efficiency of alternative surface water treatment processes and water infrastructure.

Table 2 takes sources from various reputable names for water standards, such as the World Health Organisation (WHO) the United States Environment Protection Agency (USEPA) and the National Health and Medical Research Council, Australia (NHMRC, 2011; WHO, 2009, 2016), to find the acceptable standards of the

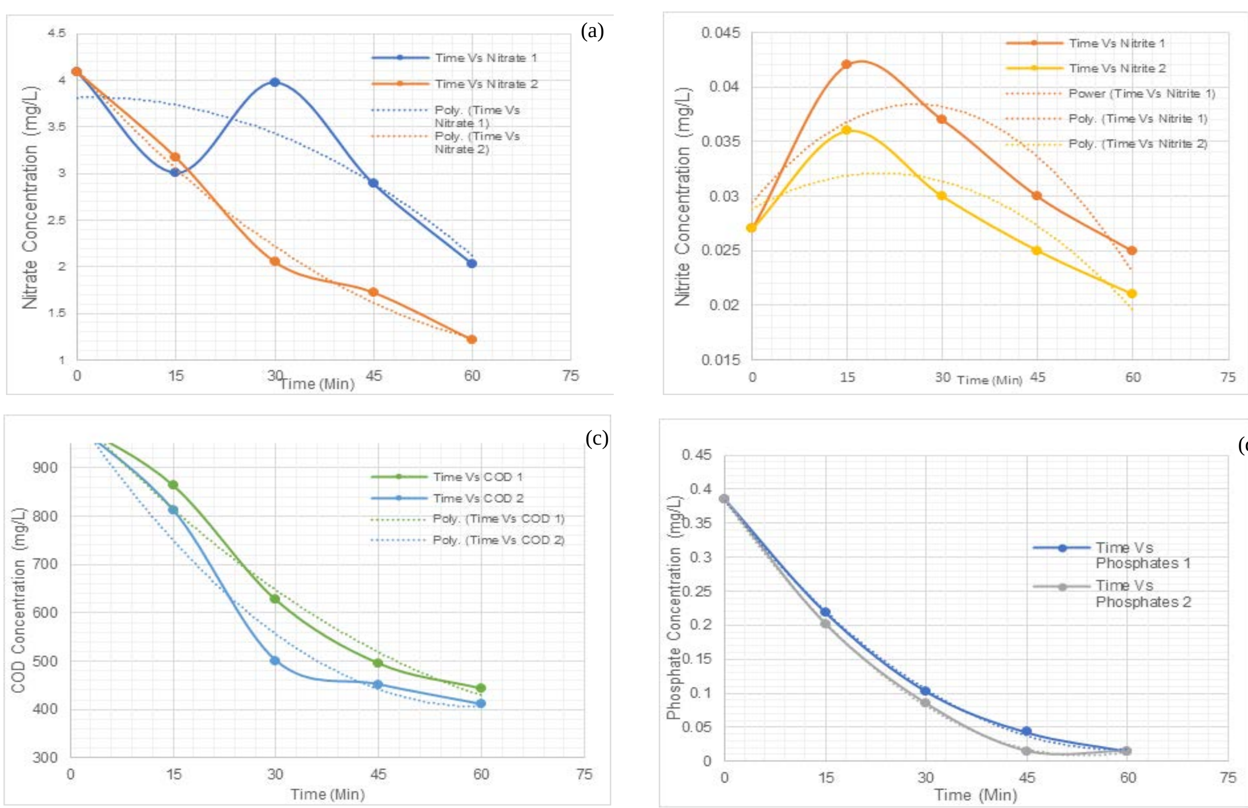

Figure 3. (a) Effluent Nitrate concentrations and polynomial best fit curves, (b) Nitrite Concentrations (mg/L) and polynomial best fit curves, (c) Chemical Oxygen Demand (COD) outflow measurements (mg/L) and (d) Phosphates outflow concentrations and polynomial curves (Period of analysis: September 2015-August 2017)

Table 2. Comparing the Effluent Remediated River Water Quality parameters against that of Drinking Water

Pollutant	Drinking Water Standard * (mg/L)	Achieved Effluent Standard (mg/L)
Ammonia	0.5	<0.015
Nitrite	<3.0	0.0098
Nitrate	< 50	0.48
COD	0	388
Phosphate	<0.1	0.015
pH	6.5-8.5	4.3

*Data adapted from WHO (2009; 2016)

pollutants in drinking water. This information is contrasted against the pollutant levels achieved after this photo-Fenton treatment process to deduce where this effluent source lies in terms of how potable the water is.

The data collected on the pollutants tested show acceptable levels of ammonia, nitrites, nitrates, and phosphate levels, although the COD and pH values were out of range at times and fluctuated. The recommended WHO concentrations of Nitrates (< 50 mg/l) were well achieved from the average effluent concentrations of 0.48 mg/l in this study as presented in Table 2. Other physical factors such as total suspended solids, total dissolved solids and turbidity were not tested for, although based on the visible colour of the effluent source it can be deduced that the physical water quality was not quite up to the required standards for potable water consumption. To make this process feasible for the St. Mary's Island development, the photo-Fenton test would have to be preceded by screening and aeration systems to reduce the physical parameters before being treated by the photo-Fenton reaction to treat the chemical impurities, followed by the addition of lime and shock chlorination. The chain of processes as described is nothing short of a typical wastewater chain, and as such, this reactor design as the sole treatment may not be able to produce potable water from a river source.

The experimental study showed that the chemical balance has more of an impact on effectiveness of treatment than any sub-variables such as the build of the reactor or the UV influx. This research project demonstrated that the reaction is successful at higher concentrations of H_2O_2. The reactor may use computer automation to regulate the quantities of chemicals being added to a batch of water. On top of this, the reactions are kept at optimal removal efficiency rates since the concentration of chemicals can be changed in fine increments, compared with human input.

Based on the results from the laboratory and pilot-scale study, the photo-Fenton process can reduce the concentration of positively charged chemical ions in river water, stormwater, or wastewater if the water sample has a low turbidity and clearer colour. It is a cost-efficient process, when compared to energy-intensive processes such as Reverse Osmosis or other tertiary treatments that require expensive membranes and high pressures. It is also efficient at removing protozoa (such as Cryptosporidium). The rise of wastewater treatment works primarily features a computer-automated photo-Fenton reaction that is combined with simple pre-screening, aeration and post-treatment with lime and shock chlorine to provide cheap potable water.

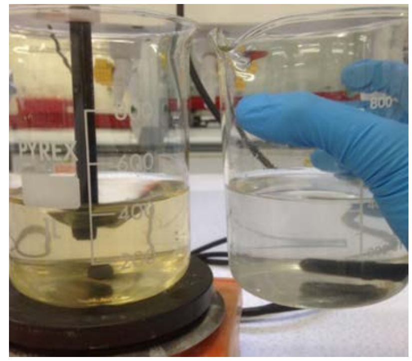

Figure 4. Untreated Medway River Water (*left*) compared to Treated River Water (*right*) (Period of analysis: September 2015-August 2017)

5. Conclusions and Recommendations

The borosilicate serpentine glass pipeline connections with self-tightening sealing bends provided very good air and water pressure sealing during this study. The initial trial and error assessment found the optimal chemical dosage and concentrations for the best removal efficiency taking a 100:1 H_2O_2: Fe^{2+} ratio as the starting point. The study demonstrated that the ratio of photochemicals is very influential to the success of other variables and thus paramount importance falls on finding the ideal concentrations and conditions. The project demonstrated ways of reducing the physio-chemical parameters in satisfying drinking water standards of the USEPA, WHO, DWI, and NHMRC.

Several conclusions were made from this research project. These are as follows:

- Under the conditions set by this research project, a smaller diameter of piping yields the best removal efficiencies of pollutants.
- An accurate chemical balance of H_2O_2: Fe^{2+} has more of an impact on the effectiveness of treatment than the use of UV radiation.
- The ideal H_2O_2: Fe^{2+} ratio for the treatment of river water is close to 100:1 mg/L.
- The impact of semi-variables such as diameter of pipe and UV influx on the effectiveness of treatment were not noticeable compared to the effect of changing the photo-Fenton chemical ratio.
- The photo-Fenton processes' removal efficiency is directly proportional to the remaining H_2O_2 concentration, as the reaction proceeds.

The photochemical balance has more of an impact on effectiveness of treatment than any sub-variables such as the build of the reactor or the UV influx. This project demonstrated that the reaction is successful at higher concentrations of H_2O_2. A solar photoreactor may use computer automation to regulate the quantities of photo chemicals being added to a batch of river water. This technology has been implemented into the Bewl water and wastewater treatment works in England Kent, the UK and drastically reduced the need for operative supervision.

The photochemical reactions are kept at optimal removal efficiency rates since the concentration of chemicals can be changed in fine increments, compared to human input. The Photo-Fenton process can reduce the concentration of positively charged chemical ions in river water and wastewater if the water sample has a low turbidity and colour. Pre-screening the test sample to remove sedimentation may improve results. For this experiment, the concentration of chemicals used does not reduce the turbidity of the effluent source, and so the presence of sediment in the water sample is pointless for further study. It would be recommended to conduct further tests to compare the water pollutant levels over time in tap water, river water, and finally pre-treated river water. This would give a benchmark trend line for the pollutant value, and results will not only show the effect that the photoreactor has on the treated river water, but also at what length of treatment is needed to reach the same pollutant levels as that in clean water.

Further experiments should be used to find the photochemical concentration of best removal efficiency, taking a 100:1 H_2O_2: Fe^{2+} ratio as the starting point. This project demonstrated that the ratio of chemicals is influential to success than any other variable, and so paramount importance falls on finding this ideal concentration. Besides, studies are required to find a way to reduce the physical parameters that were not tested in this project (TSS, TDS, BOD, turbidity, and colour) to satisfy drinking water standards of the USEPA, WHO, DWI and NHMRC. Combining automation and sufficient reduction of physical, chemical, and biochemical pollution parameters using a photo-Fenton reactor would reduce the need for extra infrastructure, whilst still providing potable water which may be a significant step forward for providing developing countries with drinkable water.

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