CDI WORKING PAPER SERIES

Treatment of Drinking Water in Vingunguti – Can Solar Technologies Help?

WP # 05/2020

Bright Nsolebna Jaato

University of Cambridge

Cambridge Development Initiative
CUSU, 17 Mill Lane
Cambridge CB2 1RX
United Kingdom
www.cambridgedevelopment.org

Cambridge Development Initiative Working Papers

The Cambridge Development Initiative (CDI) Working Paper Series, launched in 2018, draws together research volunteers from the University of Cambridge as well as academics, policy makers and practitioners beyond, to think critically and innovatively about the issues that are central to CDI's work in Dar es Salaam, Tanzania. The scope of the working paper includes education, health, entrepreneurship and WaSH, with special relevance to the East African context.

The CDI working paper series is a collection of papers, peer-reviewed, and aimed at collaborative and cross-disciplinary research. The series includes papers presented by the CDI research volunteers from the Research Team and occasional papers written by external advisers and experts. The CDI Research Team also welcomes papers from academics working on fields that relate to the CDI research agenda.

Series Editor 2020: Gauhrishi Narang, Research Director (UK), CDI
Publisher: Cambridge Development Initiative, Cambridge, UK

For expression of interest in contributing to the series or any other queries, contact:
research@cambridgedevelopment.org

Treatment of Drinking Water in Vingunguti – Can Solar Technologies Help?

Jaato, B. N.

Abstract

The supply of safe drinking water is one of the most important challenges of developing countries throughout the world. Waterborne disease is perhaps one of the most preventable types of communicable diseases and yet it has been ranked as the leading cause of death in Africa. Simple and affordable technologies can be used to purify water and thus curb the ever-increasing rate of waterborne diseases.

In this study, we demonstrate that the decomposition of organic contaminants (Methylene Blue) in water using SODIS can be greatly improved by incorporating photocatalysts. By depositing silver nanoparticles unto the surface of TiO_2-precoated glass beads and zeolite materials, a methylene blue degradation of 87.64 % and 51.42 % (in 60 minutes) was observed respectively. The materials also display high potency for pathogen inactivation.

The technique used is simple, low cost, scalable, and environmentally friendly, and can also be replicated in developing countries.

Table of Contents

List of Tables

List of Figures

Introduction

Water and Health

Water safety and quality are essential to human development and well-being.[1–4] Access to safe water is one of the most effective ways to promote health and reduce poverty,[3,4] however, it should not be forgotten that water is also a potential vehicle of disease transmission.[5] Waterborne diseases are perhaps one of the most preventable types of communicable diseases[5–7] and yet were ranked as the leading cause of death globally, with Africa being the greatest contributors to the death toll.[6,8] Waterborne diseases are also known as intestinal diseases because they affect the intestinal tract. When pathogens excreted in the faeces of an infected person is unconsciously ingested by another person (in the form of contaminated water), the cycle of the disease can continue, possibly in epidemic proportions.[5] The goal of water treatment, therefore, is to take out all existing contaminants from the water or to reduce the concentration of these contaminants so that water becomes fit for use.[5,8,12] The most widespread water-borne diseases are cholera, diarrhoea, dysentery, hepatitis A, typhoid, and polio.[1,2,5,6] Water-borne diseases can, however, be prevented, at least partially, by treating the water at the household before consumption. The application of simple sanitary principles and technology can help to virtually eliminate serious outbreaks of waterborne diseases.[5]

Water pollution can be defined as a manmade alteration of the physical, biological, and radiological integrity of water.[5,9] One of the challenges of the 21st century is in dealing with the unprecedented growth in waste production which commensurate with the increases in population growth and industrialization.[10,11] Unfortunately, most of the waste end up in freshwater bodies due to unplanned urbanization and anthropogenic activities, which causes serious problems not only to human life but animals too.

The UN General Assembly in July 2010 recognized the human right to water and sanitation and acknowledged that clean drinking water and sanitation are essential to the realization of all human rights[13]. This implies that everyone has the right to sufficient, continuous, safe, acceptable, physically accessible and affordable water for personal and domestic use. Besides, the Sustainable Development Goal target 6.1 calls for universal and equitable access to safe and affordable drinking water[14].

In this report, simple but effective, environmentally friendly and less expensive technologies that could be implemented in the treatment of water, particularly in developing countries, are identified.

The case of Vingunguiti, Tanzania

Vingunguti is an administrative ward of Ilala District of the Dar Es Salaam region with approximately 100,000 residents.[15] The shanty nature of this ward (and other similar wards in Tanzania) makes it difficult for the government to send social and economic infrastructure due to the lack of space and accessibility.[16] In the informal settlement of Vingunguiti, the construction of traditional sewerage systems is hampered by several factors including the high cost of construction, a high water table and excessively high fees associated with adequate waste disposal.[15] This has resulted in sewage overflows which pollute the water bodies (especially during rainy seasons) used by the inhabitants. The frequent outbreaks of water-borne diseases such as cholera, malaria, dysentery and typhoid in Tanzania, can be directly linked to the unscientific methods of waste disposal.[15,16]

The Water, Sanitation and Hygiene (WaSH) project of the Cambridge Development Initiative (CDI) which started in 2014, aims to improve access to sanitation in order to reduce the occurrence of various waterborne diseases in Vingunguiti. To achieve this aim, previous CDI WASH volunteers facilitated construction of four simplified sewerage routes in to improve the living standards of the Vingunguti inhabitants.[15] Adding to previous successes, and for the first time in CDI, we investigate the possibility of harnessing the single inexhaustible energy source of nature - the sun, to purify drinking-water in Vingunguiti.

Recommended Household Water Treatment Methods

Some simple but effective household water treatment methods recommended by UNICEF for water disinfection in developing countries include[17]:

- Solar water disinfection (SODIS): Utilizes the combined effects of ultra-violet radiation and heat from the sun to kill most pathogens in water. Disinfection is achieved within 6 hours to 2 days, depending on sunlight intensity and water turbidity.

- Solar pasteurization: This method effectively eliminates pathogens regardless of the water turbidity. This practice incorporates solar reflectors or insulators to reach temperatures of 60°C or more. A water pasteurization indicator (WAPI) is used to ensure that the pasteurization process is complete. Three hours is required for complete pasteurization.

- Bio-sand filters: This method is used to remove pathogens through a combination of physical and biological processes.

- Chlorination: This is a common technology and involves adding chlorine to drinking water to disinfect it and kill germs. Chlorine is available as sodium hypochlorite solution (NaOCl) or solid calcium hypochlorite ($Ca(OCl)_2$).

- Low-cost ceramic filters: These are porous fired-clay gravity-based filters. They can be impregnated with silver to improve efficiency.

Several studies show that SODIS is a simple, low-cost water treatment methods that can be used in areas that receive a high amount of solar radiation. Consequently, this method is often used in rural areas of developing countries that are in the proximity of the equator, like the Republic Union of Tanzania. [17, 18] Hence in this paper, we investigate simple ways to improve the efficiency SODIS, using photocatalysts.

Solar Water Disinfection (SODIS)

SODIS is a simple, low-cost, point-of-use drinking water treatment method that was developed in the 1980s.[19,20] In 1991, the Swiss Federal Institute for Environmental Science and Technology began to investigate and implement SODIS as a household water treatment option to prevent water-borne diseases in developing countries.[12,17,19–21] Since then, the method has been promoted as a stand-alone intervention and as one component in broader WASH programs.[17]

The SODIS concept is to utilize energy from the sun to produce small quantities of drinking water at the household level.[20,21] Solar energy is profusely and universally available free of cost and can be conveniently exploited to offer a simple, efficient and sustainable water treatment option. Pathogens (bacteria, virus, or other microorganisms that can cause disease) present in water are vulnerable to two effects of the sunlight: radiation in the spectrum of UV-A light (wavelength 320-400 nm) and heat (which increases water temperature).[12,19,22] It is the synergetic or combined effect of these two solar components that increase the mortality of the microorganisms in water.[19,23]

The SODIS Method

The SODIS method comprises the four basic steps listed below:

- Wash of Plastic Bottle: PET or glass bottles are recommended for SODIS. Bottle(s) must be 2 litres in volume or smaller, must be clean and transparent. All plastic and paper labels must be removed and bottle washed well with soap.
- Fill Plastic bottle with water: Potentially contaminated and less turbid water is filled into the bottle. If the turbidity of the water is high, it must be pretreated (by filtration) before filling into the PET bottle.
- Expose bottle to the sunlight: The bottle is then exposed to sunlight for at least 6 hours including noon hours on mostly sunny days. SODIS should not be used on days of continuous rainfall.
- Store water: Treated water is stored in the bottle until consumption in order to avoid re-contamination.

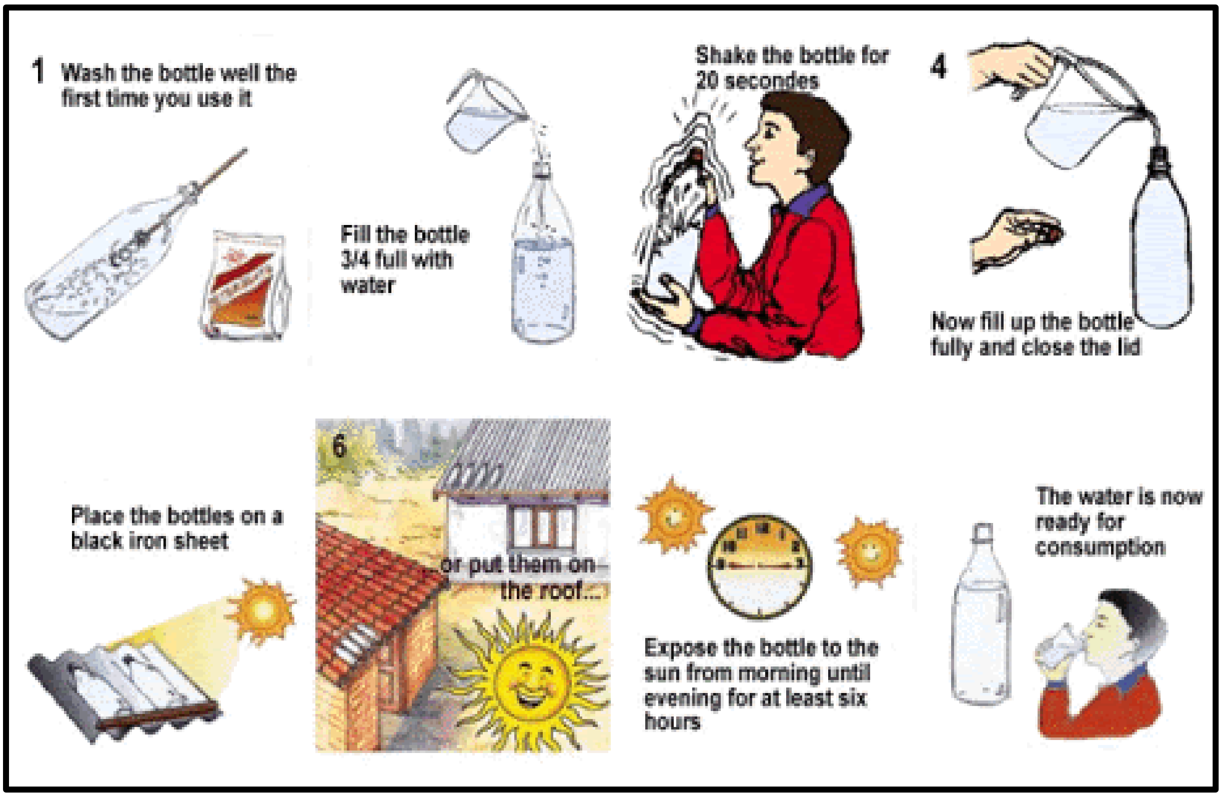

Figure 1: Pictorial representation of the stages involved with the SODIS method. 24

Benefits and Drawbacks of SODIS

Benefits

The benefits of SODIS include[20,23]:

- Improves the microbial quality of drinking or cooking water.
- No adverse effect on the taste of the water.
- Easy to understand and apply. Can serve as an entry point for health and hygiene education.
- No cost to the user after obtaining plastic bottles. Does not require large and costly infrastructure and therefore easily replicable in self-help projects.
- Recontamination is unlikely if the water is stored in SODIS bottle.
- Depends entirely on energy from the sun. Hence reduces the need for traditional energy sources such as firewood and kerosene/gas.

Drawbacks

The drawbacks of SODIS include[20,23]:

- Dependent on sufficient sunlight.
- Dependent on a significant number of clean plastic bottles.
- The relatively high treatment time required.
- Requires clear water or water of low turbidity. Highly turbid waters require pretreatment.
- Not useful for the treatment of large volumes of water.

Technical Aspect of SODIS

Mechanism of SODIS

The killing of pathogens in water through the direct effects of solar irradiation is a phenomenon that takes place in the upper layer of surface water bodies and has been harnessed for the disinfection of drinking water. The killing of the pathogen during this process is a result of the direct or mediated damage to proteins and the DNA of these dangerous organisms. The sections of the solar spectrum utilized during this process belong to the UV-B, UV-A and possibly lower visible range.

The three effects of solar radiation known to contribute to the killing of pathogens are:

1. UV-A has a lethal effect on human pathogens present in water. The radiation interacts with the DNA, nucleic acids and enzymes of the living cells, changes their molecular structure and subsequently lead to cell death. [21,22]

2. UV radiation reacts with oxygen dissolved in water to form highly reactive oxygen species (ROS), e.g. super-oxides, hydroxyl radicals, and hydrogen peroxides. These ROS then react with and damage the DNA or proteins of pathogens. [20–22]

3. Infrared radiation heats up water and causes pasteurization (thermal inactivation) when the temperature is above 40 degrees Celsius. At temperatures above 50 degrees Celsius, a synergetic effect of temperature and UV radiation occurs which strongly enhances the pathogen deactivation rate of SODIS. [20–22]

Factors Influencing Pathogen Removal in SODIS

The pathogen removal efficiency of SODIS under laboratory and field conditions has been investigated by several research groups.[19,23] Findings from these studies indicate that the efficiency of SODIS depends factors which include the following:

Type of Pathogens

SODIS has been shown to effectively inactivate microbial pathogens in the form of viruses, bacteria, fungi, protozoa, and helminth.[25] Table 1 below gives an overview of the waterborne pathogens that have been successfully inactivated using SODIS and the corresponding illnesses associated with the pathogens. [6,7,18,25]

Table 1:Waterborne pathogens that have been determined to be inactivated by SODIS and their corresponding illness. [25]

Type of pathogen	**Species**	**Illness/Symptoms**
Virus	*Norovirus*	Diarrhea
	Polio	Polio
	Rotavirus	Diarrhea
Bacteria	*Salmonella typhi*	Typhoid fever
	Vibrio cholerae	Cholera
	Shigella	Diarrhea
	Escherichia coli	Diarrhea

	Campylobacter	Diarrhea
	Yersinia enterocolitica	Diarrhea
Fungi	*C. albicans*	Candidiasis
	Fusarium sp.	Mycotoxicosis
Protozoa	*C. parvum*	Diarrhea
	Giardia sp.	Giardiasis
Helminth parasites	*Ascaris sp.*	Ascariasis

Irradiation Intensity:

The intensity of solar radiation is the amount of solar power per unit area, often expressed in W/m^2. To ensure that pathogens are completely inactivated during the SODIS process, the container needs to be exposed to a sufficient amount of solar radiation intensity.[7,18,25,26] A minimum solar radiation intensity of 500 W/m^2 and exposure of containers for at least 3 hours has been recommended by Eawag for the effective inactivation of pathogens. [25]

The factors affecting the intensity of solar radiation are the atmospheric conditions and the geographical latitude. As a rule of thumb, areas with a latitude between -30 to +30 (Figure 2), receive adequate solar radiation for the SODIS method. [25,26] This indicates that most African countries including Tanzania are well positioned geographically to exploit the method of SODIS for water purification.

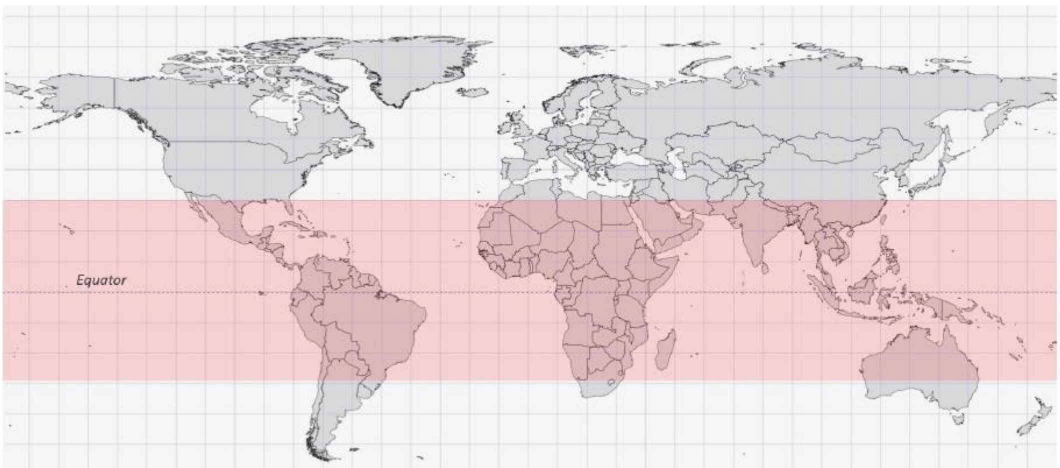

Figure 2:The SODIS method is applicable in the part of the world with a geographical latitude of ±30, which is shown in pink. [25]

Turbidity

Turbidity is a unit of measurement that quantifies the degree to which light traveling through a water column is scattered by the suspended organic (including algae) and inorganic particles. [5] Some studies suggest that suspended particles absorb and scatter UV and visible radiations and reduce the disinfection efficiency of the solar radiation. Thus, diminishing the pathogen removal efficiency of SODIS. [19]

Figure 3:Pictorial representation turbidity.

The scattering of light increases with increasing turbidity. [5] From Figure 2 above, there is an increase in turbidity from left to right, which is expected coresponds to increased dispersion of solar radiation. A simple way to determine the turbidity is by placing the bottle of water on top of a newspaper headline and checking if the text is readable when read from the neck of the bottle through the water. If the text readable, then SODIS can applied directly - if not readable, the turbidity of the water should be reduced by cloth filtration, sand filtration, flocculation or allowing particles to settle and then decant. [6,18,25,26]

Material and Size of Bottles:

The material (bottles) used for SODIS must satisfy two conditions: must have high transmittance for UV radiation and also be inert enough not to allow the leaching of dangerous chemicals into the water. [20] Polyethylene terephthalate (PET) is an inert plastic material universally used for food packaging.[20,25,26] PET materials or bottles are recommended for SODIS because they fulfill the above conditions and also because of their wide availability in low and middle-income countries. [20]

The geographical location and the wide availability of PET bottles in Tanzania make the use of SODIS an economical and viable alternative for water treatment at the household level. The next section focuses on the use of photocatalysts to improve the efficiency of SODIS.

Enhancing SODIS Technology using Photocatalysts

The use of photocatalysts to enhance the efficiency of SODIS for water treatment have attracted much attention in recent times because of their unique ability to degrade a wide variety of pollutants in water (e.g. of these pollutants include pathogens, organic materials, organic acids, pesticides, dyes and crude oil). [27] A photocatalyst is defined as a material which decomposes harmful substances using energy from the sun. [19,28]

How the photocatalyst work

Four important steps are involved when a photocatalyst is irradiated with light of wavelength equal or greater than its band gap:

a. Energy is absorbed resulting in the promotion of electrons from the valence band to the conduction band, resulting in the formation of electron-hole pairs (e^- and h^+).
b. The charge carriers (e^- and h^+) are separated.
c. Charge carriers (e^- and h^+) migrate to the surface of photocatalyst.
d. On the surface, they can participate in redox reactions (leading to decomposition of harmful substances) at the particle-solution interface.

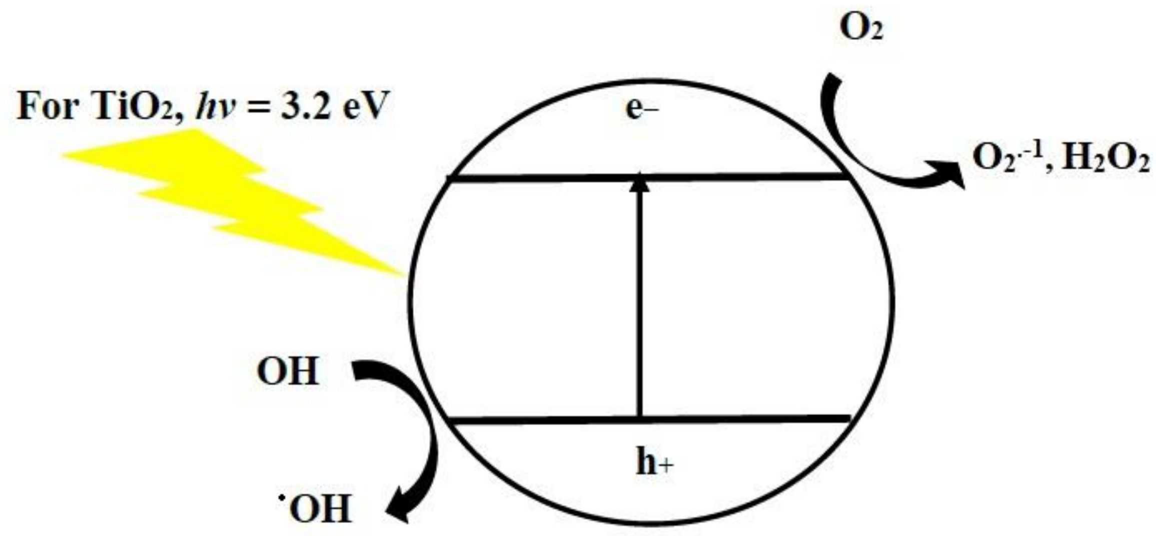

Figure 4:Schematic representation of the mechanism of photocatalysis on titanium dioxide particles.

The reactive oxygen species (ROS) produced (.OH, H_2O_2, $O_2{.}^{-1}$, etc.), are chemically reactive, species that can decompose a large variety of chemical contaminants in water and also causing fatal damage to microorganisms. [27] [24]

Titanium dioxide is the most explored photocatalyst for water treatment due to its non-toxic, high photo-stability, anti-corrosive, sensitivity to UV radiation and environmentally friendly nature. [29–33] By modifying titanium dioxide with other elements, it is possible to enhance their photocatalytic activity [34, 35] and hence increase its efficiency to disinfect water.

Experimental Work

At the Department of Materials Science and Metallurgy Department, Cambridge, common kitchen equipment like microwaves and ovens were used to prepare titanium dioxide-based materials that efficiently purify contaminated water. The materials were immobilized onto various substrates (glass beads and zeolite) and their ability to degrade methylene blue (the model pollutant) was determined. The photo-activity of the materials (on each of the substrates) were optimized by varying various preparatory parameters.

In the experiment, silver nanoparticles are deposited onto the surface of TiO_2-precoated substrate of glass beads and zeolite. Silver nano-particles are powerful at killing pathogens in drinking water,[36] and also known to enhance the photocatalytic activity TiO_2.[37] The deposition was accomplished by the chemical reduction of $AgNO_3$ using formaldehyde as reducing agent. By varying the following parameters: concentration of $AgNO_3$, volume of formaldehyde, furnace conditions and microwaving time, the best performing silver decorated materials were obtained.

Materials

Silver nitrate ($AgNO_3$), Formaldehyde, TiO_2-precoated glass beads, TiO_2-precoated zeolite and Methylene blue (MB).

Procedure

For the typical experiment, different masses of $AgNO_3$ were measured and dissolved completely in 20 ml of deionized water to produce different concentrations of $AgNO_3$ solution (0.1 M, 0.01 M, 0.001 M, 0.0001 M, 0.0005 M, 0.0025 M, 0.00001 M and 0.000001 M). 0.12 g of the TiO_2-precoated materials were transferred into separate vials and specific volumes of the prepared $AgNO_3$ solutions and formaldehyde were added. By maintaining a constant final volume (0.5 ml) throughout the experiment, the volumes of $AgNO_3$ solutions and formaldehyde were varied to obtain the best performing material. The vails were microwaved for 5 minutes to ensure deposition of silver unto the surface of the TiO_2-precoated material and complete evaporation of solvent. The resulting materials were sintered in the oven for 30 minutes at 300 $_o$C. The materials were taken out of the oven and kept in the fume-hood to cool for an hour, and then tested for their photocatalytic performance.

Photo-degradation Experiment

The photo-degradation ability of both photocatalyst materials; TiO_2-precoated materials and Silver-decorated-TiO_2-precoated materials, were determined using UV-light assisted dye degradation experiments. Methylene blue (MB) was selected as the model compound for the experiment and 5 ml of the MB stock solution (5 mg/L) was mixed with 0.12 g of the each photocatalyst material into culture well plates. The mixture in the culture well plates were kept in the dark and under continuous agitation using a rotating disk for 60 minutes to ensure adsorption of MB molecules unto the photocatalyst surface. A control experiment, mimicking the normal SODIS, where no photocatalyst was added to the MB solution was also setup. The experiment was then designed to run for 60 minutes and absorbance data was collected at λ=660 nm every 15 minutes using a UV-Vis Spectrometer.

The rate constant for the best performing material was estimated and recorded in the **Table 3** below. The rate constant (K) is the value that quantifies the rate of a chemical reaction. [38] The higher the K value, the higher the rate and vice versa. Also, the degradation of MB solution closely follows the first order kinetics which can be described by the equation below:

$$-\ln(C/C1) = k \times t$$

Where C1 is the initial concentration, C is concentration at time t and k is the reaction rate constant. Hence the rate constant can be measured by measuring he slope of the line having the best fit with the data points. [38]

Results and Discussion

Table 2 presents the synthesis parameters that yielded the best performing $AgNO_3$ treated materials. Generally, all the materials were photocatalytic and were able to degrade MB solution. Within the measured time period (60 minutes) glass bead photocatalyst materials displayed the highest degradation of 87.64 % and 62.10 % corresponding to $AgNO_3$ treated

TiO_2-precoated material ($Ag-TiO_2$-Precoated Beads) and the untreated TiO_2-precoated material respectively (see **Table 3** and **Figure 5**). $Ag-TiO_2$-Precoated zeolite material, on the other hand, displayed a degradation of 51.42 % and the TiO_2-Precoated zeolite material showed a degradation of 42.22 % (see **Table 3** and **Figure 6**). The control experiment, where MB solution was only exposed to UV-light, showed a degradation of 6.91 %.

Table 2:Synthesis parameters for the best performing photocatalysts.

Material	Concentration of $AgNO_3$ (M)	Volume of $AgNO_3$ (ml)	Volume of HCHO (ml)	Microwave Power	Furnace Temperature
Glass Beads	0.0025	0.4975	0.0025	High	300 $_o$C(30 min)
Zeolite	0.01	0.25	0.25	High	300 $_o$C(30 min)

Table 3:Data of the relative concentration and fraction of MB degradation for each substrate before and after Silver deposition.

Material	[MB] (ppm)	Degree of Degradation (%)	Dye Degraded (ppm)	K, (min-$_1$)
$Ag-TiO_2$-Precoated Beads	5	87.64	4.38	0.0348
TiO_2-Precoated Beads	5	62.10	3.10	0.0162
$Ag-TiO_2$-Precoated Zeolite	5	51.42	2.57	0.012
TiO_2-Precoated Zeolite	5	42.22	2.11	0.009
Control Experiment	5	6.91	0.34	0.001

Legend: [MB] – Concentration of MB, Degree of Degradation (%) = [(1 - C/C1) X 100]

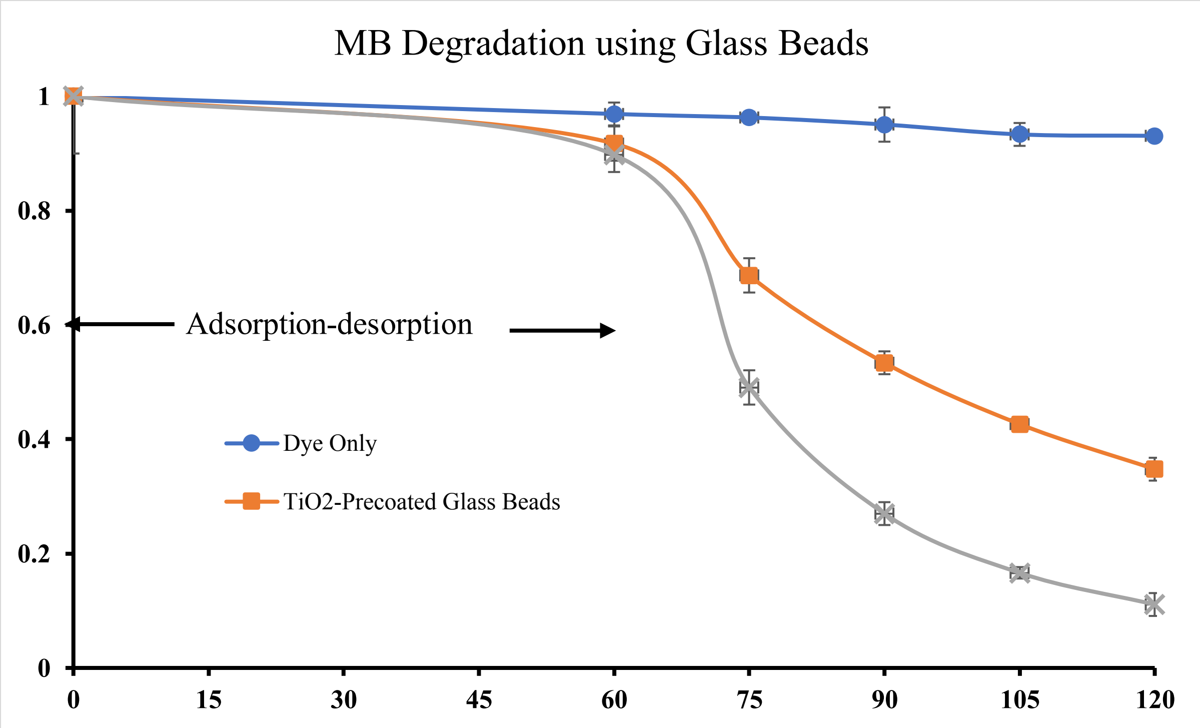

Figure 5:Time-dependent degradation profiles for all glass bead samples and control experiment (Dye Only)

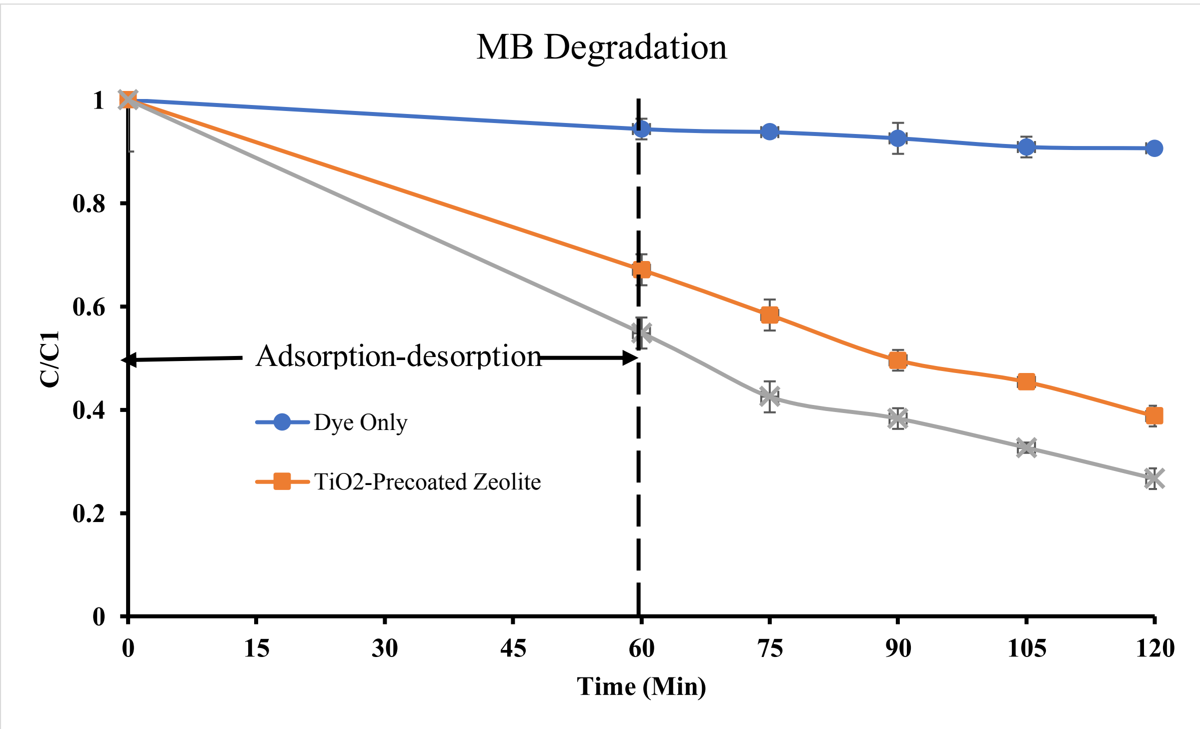

Figure 6:Time-dependent degradation profiles for all zeolite samples and control experiment (Dye Only).

Conclusion

All the materials were photocatalytic and performed better than normal SODIS. The deposition of silver nanoparticles unto the surface of TiO_2-precoated materials enhanced their photo-degradation efficiency. Generally, glass bead materials performed better than zeolite materials.

Silver decorated glass bead photocatalysts displayed the highest degradation of 87.64 % (4.38 ppm out of 5 ppm of MB) while the undecorated TiO_2-precoated glass bead photocatalysts showed a degradation of 62.10 % (3.10 ppm out of 5 ppm of MB).

Silver decorated zeolite photocatalysts displayed a degradation of 51.42 % (2.57 ppm out of 5 ppm of MB) while the undecorated TiO_2-precoated zeolite photocatalysts showed a degradation of 42.22 % (2.11 ppm out of 5 ppm of MB).

Compared with the 6.91 % degradation (0.34 ppm out of 5 ppm of MB) observed in the control experiment (which mimics that of the normal SODIS), it is clear that photocatalysts can greatly enhance the photo-degradation process of SODIS.

The silver decorated materials showed high potency for pathogen inactivation.

References

1. UNICEF & WHO. *Progress on household drinking water, sanitation and hygiene 2000-2017: Special focus on inequalities*. *Launch version July 12 Main report Progress on Drinking Water, Sanitation and Hygiene* (2019).
2. Neira, M. & Prüss-Ustün, A. Preventing disease through healthy environments: A global assessment of the environmental burden of disease. *Toxicol. Lett.* **259**, S1 (2016).
3. WHO. *Water, Sanitation, and Hygiene in Health Care Facilities Practical Steps To Achieve Universal Access To Quality Care*. (2019).
4. WHO. *A guide to equitable water safety planning: ensuring no one is left behind*. (2019).
5. Spellman, F. R. & Drinan, J. E. *The Drinking Water Handbook*. *The Drinking Water Handbook, Third Edition* (Taylor & Francis Group, 2012).
6. Prüss-Ustün, A. *et al.* Burden of disease from inadequate water, sanitation and hygiene in low- and middle-income settings: A retrospective analysis of data from 145 countries. *Trop. Med. Int. Heal.* **19**, 894–905 (2014).
7. Figueroa, M. E. & Kincaid, D. L. Household water treatment and safe storage. *Routledge Handb. Water Heal.* 221–233 (2015) doi:10.4324/9781315693606.
8. Saxena, K. S. *Optimization of Portable water treatment Technologies*. (LAP LAMBERT Academic Publishing).
9. Congress, U. S. Federal water pollution control act. *33 U.S.C. 1251 seq.* 234 (2002).
10. Ambika, S. P. P. *Environmental remediation by nanoadsorbents-based polymer nanocomposite*. *New Polymer Nanocomposites for Environmental Remediation* (Elsevier Inc., 2018). doi:10.1016/B978-0-12-811033-1.00010-X.
11. Bhat, A. H. *et al. Nanocomposite membrane for environmental remediation*. *Polymer-based Nanocomposites for Energy and Environmental Applications* (Elsevier Ltd., 2018). doi:10.1016/B978-0-08-102262-7.00015-5.
12. RS2. *Potable water specification,2nd Ed, Rwanda Bureau of standard,kigali*. (2012).
13. United Nations. The Human Right to Water and Sanitation Milestones. *Action* 1–4 (2015).
14. UNECE & WHO. The Equitable Access Score-card supporting policy processes to achieve the human right to water and sanitation. *United Nations* (2013).
15. Angelidakis, B. E. & Nassoro, C. WaSH 2019 Internal Monitoring, Evaluation and Learning Report. (2019).
16. Ali, M. H. & Sulaiman, M. S. The Causes and Consequences of the Informal Settlements in Zanzibar. *Shap. Chang.* 8–13 (2006).

17. UNICEF. Going to Scale with Household Water Treatment and Safe Storage (HWTS). 27 (2009).
18. Fransson, E. & Werner, A. Feasibility of SODIS as a Household Water Treatment Method in Rural Tanzania A Case Study in the Villages Bulyaheke and Mbugani. (2019).
19. Teksoy, A. & Eleren, S. Ç. Drinking Water Disinfection by Solar Radiation. *Environ. Ecol. Res.* **5**, 400–408 (2017).
20. Luzi, S., Tobler, M., Suter, F. & Meierhofer, R. *SODIS manual*. (2016).
21. Wegelin, M. Training manual for SODIS Promotion. *Lions Club* 39 (2006).
22. Wegelin, M., Ahmed, R. & Ahmed, N. 24th WEDC Conference Progress in solar water disinfection (SODIS) Sodis experiments in Karachi. 365–369 (1998).
23. Mcguigan, K. Solar disinfection of drinking water. *J. Commun. Dis.* **37**, 321–324 (2005).
24. Solar Disinfection Techniques (SODIS). https://nebzyl.blogspot.com/2011/04/solar-disinfection-techniques-sodis.html.
25. Fontán-Sainz, M., Gómez-Couso, H., Fernández-Ibáñez, P. & Ares-Mazás, E. Evaluation of the solar water disinfection process (SODIS) against Cryptosporidium parvum using a 25-L static solar reactor fitted with a Compound Parabolic Collector (CPC). *Am. J. Trop. Med. Hyg.* **86**, 223–228 (2012).
26. Oates, P. M., Shanahan, P. & Polz, M. F. Solar disinfection (SODIS): Simulation of solar radiation for global assessment and application for point-of-use water treatment in Haiti. *Water Res.* **37**, 47–54 (2003).
27. Europe, I. Photocatalysis for Water Treatment. *J. Environ. Sci. Comput. Sci. Eng. Technol.* **7**, 1–4 (2018).
28. Zhu, S. & Wang, D. Photocatalysis: Basic principles, diverse forms of implementations and emerging scientific opportunities. *Adv. Energy Mater.* **7**, 1–24 (2017).
29. Jiang, W. *et al.* Vertically Oriented TiO_xN_y Nanopillar Arrays with Embedded Ag Nanoparticles for Visible-Light Photocatalysis. *Langmuir* **28**, 5427–5431 (2012).
30. Kumar, A. A Review on the Factors Affecting the Photocatalytic Degradation of Hazardous Materials. *Mater. Sci. Eng. Int. J.* **1**, 106–114 (2017).
31. Sarkar, A. & Khan, G. G. The formation and detection techniques of oxygen vacancies in titanium oxide-based nanostructures. *Nanoscale* **11**, 3414–3444 (2019).
32. Chen, H., Yang, M., Tao, S. & Chen, G. Oxygen vacancy enhanced catalytic activity of reduced Co3O4 towards p-nitrophenol reduction. *Appl. Catal. B Environ.* **209**, 648–656 (2017).

33. Gomes, J., Lincho, J., Domingues, E., Quinta-Ferreira, R. M. & Martins, R. C. N-TiO2 photocatalysts: A review of their characteristics and capacity for emerging contaminants removal. *Water (Switzerland)* **11**, (2019).
34. Agbe, H. *et al.* Recent advances in photoinduced catalysis for water splitting and environmental applications. *J. Ind. Eng. Chem.* **72**, 31–49 (2019).
35. Fajrina, N. & Tahir, M. ScienceDirect A critical review in strategies to improve photocatalytic water splitting towards hydrogen production. *Int. J. Hydrogen Energy* **44**, 540–577 (2018).
36. Durán, N. *et al.* Potential use of silver nanoparticles on pathogenic bacteria, their toxicity and possible mechanisms of action. *J. Braz. Chem. Soc.* **21**, 949–959 (2010).
37. Coto, M., Divitini, G., Dey, A. & Krishnamurthy, S. Tuning the properties of a black TiO 2 -Ag visible light photocatalyst produced by rapid one-pot chemical reduction Tuning the properties of a black TiO 2 -Ag visible light photocatalyst produced by a rapid one-pot chemical reduction. *Mater. Today Chem.* **4**, 142–149 (2017).
38. Hernández-Gordillo, A. *et al.* Good practices for reporting the photocatalytic evaluation of a visible-light active semiconductor: Bi2O3, a case study. *Catal. Sci. Technol.* **9**, 1476–1496 (2019).