

WATER DISINFECTION USING NANOTECHNOLOGY FOR SAFER IRRIGATION: A DEMONSTRATION PROJECT IN SWAZILAND

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ABSTRACT

This case study assesses the feasibility of a point-of-use (POU), nanomaterial-enabled photocatalytic water treatment device for use in rural areas in Swaziland. Small reservoirs provide water for irrigation and community consumption, but this water is highly contaminated with human and animal wastes. A prototype fluidized bed photoreactor -- amended with nano-sized TiO₂ coated on silica beads (60 wt%) and illuminated by UV light (254 nm, 18 W cm⁻²) -- was capable of removing 99.9% of bacteria and viruses with less than 60 seconds of contact time. However, control tests showed that the majority of the disinfection was accomplished by UV light alone, with the photocatalytic material unable to significantly add to the disinfection at such short contact times. A potential benefit of using nano-sized TiO₂ photocatalyst was the removal of a model pesticide (Carbaryl) whose concentration was reduced by approximately 50% (compared to controls) with a contact time of 3 minutes. This research highlights the importance of POU water treatment systems, and demonstrates the potential feasibility and limitations of using nanotechnology-enabled small reactors to help relieve high water-related disease and mortality rates in developing countries.

INTRODUCTION

Reliable access to clean and safe water is a global challenge that will continue to grow in the next century (Brame et al. 2011). The United Nations (UN) placed

this challenge among its 2015 Millennium Development Goals with the stated objective to “halve, by 2015, the proportion of the population without sustainable access to safe drinking water and basic sanitation” (see <http://www.un.org/millenniumgoals/>). As water treatment and supply challenges continue to expand, new technologies are being tested to help reach the goal of unilateral access to safe and sustainable water. Among these technologies, point-of-use (POU) treatment processes are promising alternatives to large-scale, centralized treatment systems (Kallman et al. 2011; Lantagne et al. 2011). POU treatment processes do not require large infrastructure or high construction costs, and do not suffer from water quality degradation during distribution (Majuru et al. 2011). Nanomaterials may be advantageous for POU treatment technologies because of their extremely high surface area and unique mechanical, electronic, photonic, and magnetic properties (Qu et al. 2012). In addition to individual and community use, nano-based water treatment systems have great potential to address challenges in sustainable agriculture, food safety and food security (NANOAGRI-2010).

Rice University and the Food and Agriculture Organization of the United Nations (FAO) collaborated to test the feasibility of a POU, nanotechnology-enhanced water treatment system for rural farms in Swaziland. Small reservoirs created by earthen dams built by the Swaziland Agricultural Development Program (SADP 2011), an E.U.-funded project to improve “sustainable food security and an improved

quality of life for rural households in Swaziland” (FAO 2012), provide a significant resource for agricultural irrigation. This ready access to irrigation water has provided rural communities with the ability to create small garden plots, which can be used to grow produce for personal or commercial use. However, water in this type of reservoir is frequently contaminated by waste discharge from upstream, runoff from large-scale agricultural sites, and the direct introduction of animal wastes from local livestock (Hanjra et al. 2012). The water at these sites -- used both for irrigation and as a drinking water supply -- exceeded over 100 times the national regulatory levels for microbiological contamination (Table 1). The potential benefit of improved irrigation by the SADP dam project is countered by the risk of disease from water contamination. Thus, we explored photocatalytic, point-of-use water treatment options to alleviate the risks inherent in this contaminated water supply.

Photocatalysts transfer the energy from light into chemical energy through charge transfer, redox (reduction/oxidation) reactions and other electrochemical processes (Fujishima and Honda 1972; Fujishima et al. 2008; Hoffmann et al. 1995). For example, in semiconductor (TiO₂) photocatalysis an incoming photon with energy equal to or greater than the bandgap energy of the semiconductor creates an exciton (electron/hole pair) (Figure 1). This energy can then be transferred to the material surface and participate in surface redox reactions resulting in the formation of reactive oxygen species (ROS). Different photocatalysts

produce different ROS including hydroxyl radicals (•OH), superoxide (O₂⁻¹) or singlet oxygen (¹O₂), which can then react with target contaminants such as bacteria, viruses or organics (Toepfer et al. 2006).

The objective of this project was to design, build and test a nano-enhanced photocatalytic demonstration unit with the ability to treat the high levels of microbiological contamination in the irrigation water from these reservoirs, as well as potentially treat other organic contaminants (such as pesticides) present in the water.

MATERIALS AND METHODS

Photoreactor

A fluidized bed photoreactor (FBPR) was selected for this application. An FBPR uses the up flow of water through the reactor to mix photocatalyst particles, which can be illuminated internally (Figure 2). Advantages of the FBPR include extended reuse of photocatalyst (with the option to replace spent photocatalytic material), an in-line configuration that could be easily added to the existing local infrastructure, and the ability to use a wide range of photocatalysts and lamps of any wavelength rather than being limited to visible light (Colina-Márquez et al. 2010). Challenges include the need for external power for illumination (solar illumination has a limited spectrum in the UV range and is difficult to use in an internally-illuminated reactor), the need for rapid disinfection due to the relatively short contact time, and the need for periodic replacement of bulbs and photocatalyst. Although the FBPR requires a small amount of external power (car battery or small solar panel), it provides flexibility

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TABLE 1
Selected water quality parameters from the three dams in Swaziland.

	Mcozini Dam	Lubhuku Dam	Mlawula Dam	National Standard Irrigation (Drinking)
Total coliforms (per 100 mL)	4000*	1500**	4000**	1-10 (0)
Fecal coliforms (per 100 mL)	90**	120**	160**	1-10 (0)
Turbidity (NTU)	9.0**	305**	202**	5 (5)
BOD5 (ppm)	5.5*	1.0	0.7	10 (5)
COD (ppm)	19*	23*	18*	75 (10)

* indicates value above National drinking water standards
** indicates value above National drinking and irrigation water standards

FIGURE 1

Photocatalytic ROS production mechanism. A photon excites TiO_2 , which can then transfer the energy (e.g., excited electrons, holes $[\text{e}^-]$, excitons, etc.) to water (H_2O) or oxygen (O_2) to form reactive oxygen species such as hydroxyl radical ($\bullet\text{OH}$) or super oxide ($\text{O}_2^{\bullet-}$).

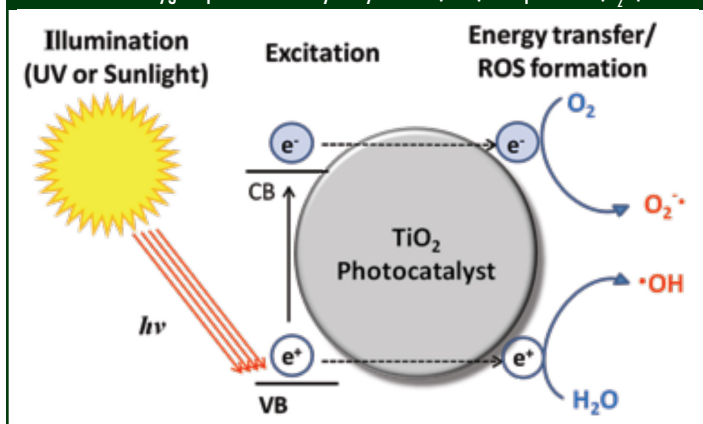
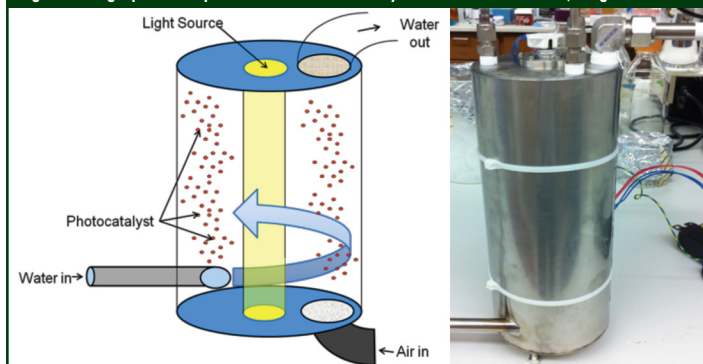


FIGURE 2

Left: Schematic representation of fluidized bed photoreactor (FBPR). The water flow suspends the attached photocatalyst material, which is illuminated within the reactor. A filter at the outflow retains the photocatalytic material in the system for continuous reuse. Right: Photograph of completed bench-scale FBPR system. Diameter=12 cm; height=26 cm.



to use bactericidal lamps to aide in the rapid removal of microbiological contaminants and ensures the necessary disinfection in the short contact time dictated by the reactor size requirements. Two identical aluminum bench-top FBPR reactors were constructed, each having an internal volume of 2.5 L. The light source is a 16W lamp encased within a quartz housing running the length of the cylindrical axis. The outflow port

has a 40- μm mesh filter to retain the photocatalyst inside the system. A step-input tracer test confirmed that the FBPR performed as a completely mixed reactor (Figure S1, Supporting Information).

Photocatalyst Materials

The following nano-photocatalysts were tested: titanium dioxide (TiO_2), a broadly available

semiconductor photocatalyst that produces mainly hydroxyl radicals and is most effective when excited by UV light; amino-fullerenes, a novel photocatalyst that produces mainly singlet oxygen and can be excited by visible light (Lee et al. 2010); and porphyrins, which have been used for photo-dynamic therapy (Ashkenazi et al. 2003; Merchat et al. 1996) and produce singlet oxygen when excited by visible light. Amino-fullerenes were synthesized as previously reported (Lee et al. 2010); the porphyrins (5,10,15,20-tetrakis(4-carboxyphenyl), $\text{C}_{48}\text{H}_{30}\text{N}_4\text{O}_8$, MW: 790.774), were synthesized and characterized according to standard procedures (Datta-Gupta and Bardos 1966). Additional purification was performed using a flash chromatography system (silica column Clarisep S-CS140120-0, 40-60 μm , 60 \AA) with chloroform and methanol solvents for 99+% product purity (by HPLC analysis).

Each of these photocatalyst materials were attached to a silica or sand substrate. Photocatalyst attachment enables facile separation inside the FBPR, increases the photo-available surface area of the photocatalytic material (Balasubramanian et al. 2004) and reduces the risk of material release. TiO_2 was attached through a heat treatment of substrate particles dipped in powdered DeGussa P25 TiO_2 (Evonik Industries, Essen Germany) mixed with either water (heat, H_2O) or with isopropanol (heat, solvent), or attached through a sol-gel precipitation process (Chen and Dionysiou 2006; Qourzal et al. 2009). The amino-fullerenes and porphyrins (both fabricated at Rice University) were attached to the silica substrate by covalent amide bonds to ensure stability and eliminate photocatalyst sloughing (Lee et al. 2011). None of these materials exhibit acute toxicity, and these attachment processes limit potential exposure and therefore risk.

Illumination

We examined three types of illumination for use in this FBPR system: visible light (400-800 nm), near-UV light (UV-A, 300-400 nm) and bactericidal light (UV-C, 254 nm) using Eiko T5 4-W fluorescent lamps. Visible light is effective for fullerenes and porphyrins, and has not been shown to degrade the

bonds that attach the organic photocatalysts to the silica substrate. UV-A light is more energetic and capable of creating photo-generated ROS in TiO_2 photocatalysts. While the increased energy of UV-A light can provide an increase in degradation rates using fullerenes and/or porphyrins, repetition tests in batch reactions show that the overall efficiency of the fullerene photocatalyst decreases with repeated use (Figure 3). UV-C light is naturally bactericidal, which is a benefit for this application. It is also very effective at producing photo-generated ROS with TiO_2 , although the high energy light destroys fullerene and porphyrin photocatalysts.

Batch Tests

Initial photocatalytic tests were performed in a batch photoreactor (Lee et al. 2009) with six 4-W lamps arranged around a 50-mL quartz reaction vessel with 18 W m^{-2} illumination. Further details about this batch reactor can be found in Brame et al. 2013; and Lee et al. 2009. These batch tests helped determine ROS production rates of the various photocatalyst, substrate and illumination configurations. The process involves adding photocatalyst (0.2 g L^{-1} unless otherwise noted) and a probe compound to Milli-Q water for a total volume of 40-mL. Furfuryl alcohol (FFA) was used as a probe to measure ROS production (Lee et al. 2009). At steady state, ROS generation is proportional to the first-order degradation rate of FFA (Buxton et al. 1988). Reactions took place over the course of 2 hours with 1-mL samples taken periodically throughout the test and measured on a Shimadzu Prominence HPLC (Shimadzu Corp., Columbia MD) using a C18 column with acetonitrile and 0.1% (w/v) phosphoric acid as mobile phase. All solvents and probe compounds were analytical grade (Sigma-Aldrich-USA). First order degradation rate constants (k) were calculated with 95% confidence intervals based on observed degradation (Table 2).

A similar procedure was used for batch reactions testing the inactivation of *E. coli* and adenovirus type 2 (AV2), a highly UV-resistant, double-stranded DNA virus that is capable of infecting humans and re-

FIGURE 3

Reuse tests using the same photocatalyst for five cycles in batch reactions. For fullerenes (a): with visible light illumination there is no loss in efficiency (as measured by the degradation of furfuryl alcohol [FFA]), while with UV-A illumination there is a 50% loss in efficiency and with UV-C illumination the photocatalyst breaks down entirely. For TiO₂ (b): visible light produces very little degradation, while both UV-A and UV-C illumination are easily repeated 5 times with no loss of degradation capacity. (Test conditions: 0.2 g/L photocatalyst, [FFA]₀=1,200 μM, 23°C, pH 7).

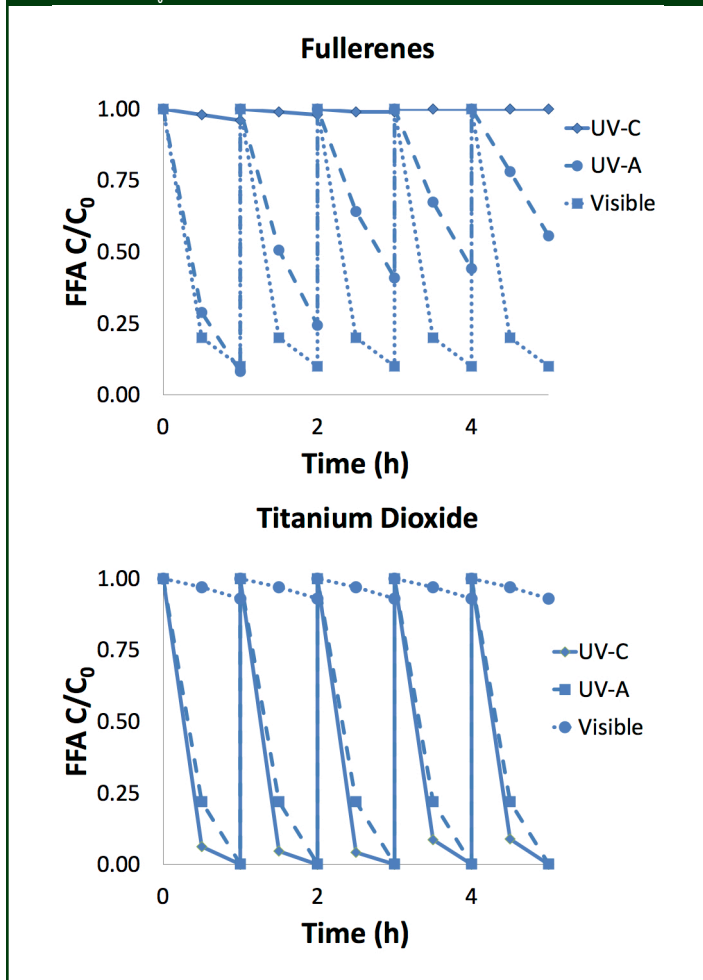


TABLE 2

First order FFA degradation rate coefficients (*k*) from batch reactions.

<i>k</i> (min ⁻¹ *10 ⁻⁴) ± one SD				
Material	Attachment	Visible Light (400-800 nm)	UV-A Light (300-400 nm)	UV-C Light (254 nm)
TiO ₂	Sand (heat, H ₂ O)	0	30±1	320±23
	Sand (heat, solvent)	0	0	330±50
	Sand (sol-gel)	0	32±3	275±20
	Silica (sol-gel)	6±1	510±80	500±30
Fullerenes	Silica	70±1	145±1	17±1
Porphyrins	Silica	10±1	20±2	0

sponsible for ~5-10% of upper respiratory infections in adults (Eischeid et al. 2009; Eischeid et al. 2011). *E. coli* was grown to exponential phase and then rinsed thoroughly to remove any residual growth media and diluted 1:40 in the batch

reaction vessel. Surviving organisms were determined using viable plate counting. Due to the short lifetime of *E. coli* exposed to UV-C light, only one of the six available lamps was used to reduce the UV exposure, with samples being taken every 20

seconds. AV2 active titer was quantified by conventional plaque assays. Virus samples were inoculated on sub-confluent A549 cell monolayers for 90 minutes. The flasks containing infected cells were then overlaid with agar-containing media, incubated 7 days, and stained with MTT to visualize plaques.

Flow-Through Tests

Continuous flow/semi-batch tests were performed in the FBPR system similar to the batch reaction described above. Tests measured degradation of FFA, *E. coli* or AV2 virus as above with samples drawn from the outflow port. DI water spiked with the test compounds/organisms was re-circulated through the FBPR until steady state was reached, then the lamp was turned on and the measurements taken. Long term tests were conducted using the same photocatalytic material in the same reactor with the same lamp for two hours each day for 60 consecutive days to mimic intended use in the field. *E. coli* and AV2 experiments were performed using the reactor in flow-through mode, while long-term FFA degradation tests utilized the reactor as a semi-batch system.

RESULTS AND DISCUSSION

Performance of Photocatalytic Materials

After testing various combinations of photocatalyst material, attachment method and light source (Table 2), sol-gel TiO₂ attached to silica under UV-C light was chosen for this application. There was little photocatalytic efficiency difference between UV-A and UV-C illuminated sol-gel TiO₂, and UV-C light requires only slightly more energy than UV-A while it is inherently bactericidal, thus aiding in disinfection. It was necessary to use an attached photocatalyst to easily retain the photocatalytic material inside the reactor.

A range of photocatalyst concentrations were tested to determine whether the photocatalyst material increased the already significant disinfection of UV-C illumination alone. Higher photocatalyst loading increases ROS production, which increases disinfection poten-

tial. However, light scattering from higher photocatalyst concentrations in the water decreases disinfection by UV-C. These competing mechanisms result in an optimal photocatalyst concentration. Specifically, the photocatalyst material does increase *E. coli* removal up to a loading of about 1.5-2 g L⁻¹ (Figure 4). Each data point shows the differential *k* value (decay with UV-C light and the photocatalyst minus the decay with UV-C light alone) for a given loading. A positive differential *k* value indicates that the photocatalyst is increasing *E. coli* removal efficiency through ROS generation while a negative differential *k* value indicates that the photocatalyst reduced the overall efficiency of the UV-C light through self-scattering. Above a loading of 2 g L⁻¹ the photocatalyst has an inhibitory effect on *E. coli* inactivation. We chose a loading of 0.2 g L⁻¹ to use in the FBPR system based on these results. This loading provides a significant increase in efficiency, while still using a relatively small amount of photocatalyst, which is more cost efficient.

Previous work using TiO₂ and UV-A illumination indicates that there is often a “shoulder effect” in which there is a lag before the ROS-induced disinfection mechanism takes effect (Cho et al. 2004). However with UV-C illumination, 3-log disinfection is accomplished in only 30-60 seconds, leaving little time for ROS to inactivate the bacteria before disinfection is accomplished by the high intensity light. Although the increase in disinfection rate afforded by the photocatalyst in the TiO₂/UV-C system is two to three orders of magnitude higher than rates reported for TiO₂/UV-A systems, which typically require contact times of 10-100 minutes (Cho et al. 2004; Kikuchi et al. 1997; Maness et al. 1999), it represents an increase of only 5-10% above the degradation rate with UV-C alone.

Accordingly, Figure 5 shows the flow-through inactivation of *E. coli* in the FBPR with UV-C light alone and with the addition of the photocatalyst. In both cases the FBPR accomplishes 2-log (99%) removal in under 30 seconds of exposure time, with the photocatalyst-enhanced treatment being slightly more effective (*p* = 0.07). The disinfection rate of the

FIGURE 4

Effect of photocatalyst loading on *E. coli* inactivation kinetics. The differential k value is the first-order degradation rate coefficient with photocatalyst minus the rate coefficient without the photocatalyst (control). A positive differential k value indicates that the photocatalytically-generated ROS is increasing *E. coli* removal, while a negative differential k value indicates that the scattering effect of the photocatalyst is reducing the overall degradation efficiency of the UV-C light (254 nm, 18 W/m² illumination, bacteria loading=10⁶ CFU/mL, 23°C, pH 7).

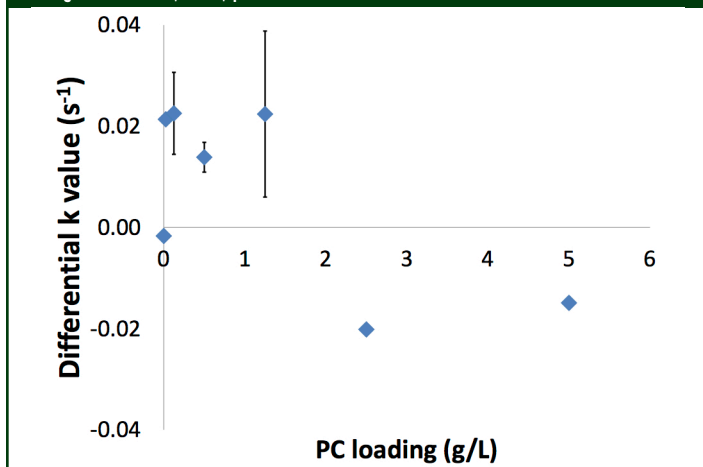
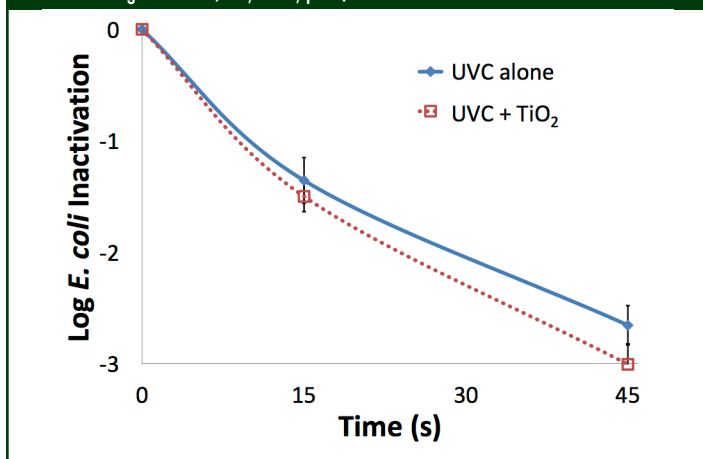


FIGURE 5

Log removal of *E. coli* in the FBPR system with UV light alone and with the addition of the silica-attached photocatalyst (PC) material (0.2 g/L TiO₂, 254 nm, 18 W/m² illumination, bacteria loading = 10⁵ CFU/mL, 23°C, pH 7).



treatment with photocatalyst was 6% (0.018 min⁻¹) higher than that of the treatment with UV alone, consistent with the batch loading tests (0.02 min⁻¹ increase, Figure 4). When the FBPR was run as a flow-through reactor, with contaminated influent passing entirely through the reactor with the lamp on, there was no surviving *E. coli* measured in the effluent with or without photocatalyst present, regardless of influent concentration.

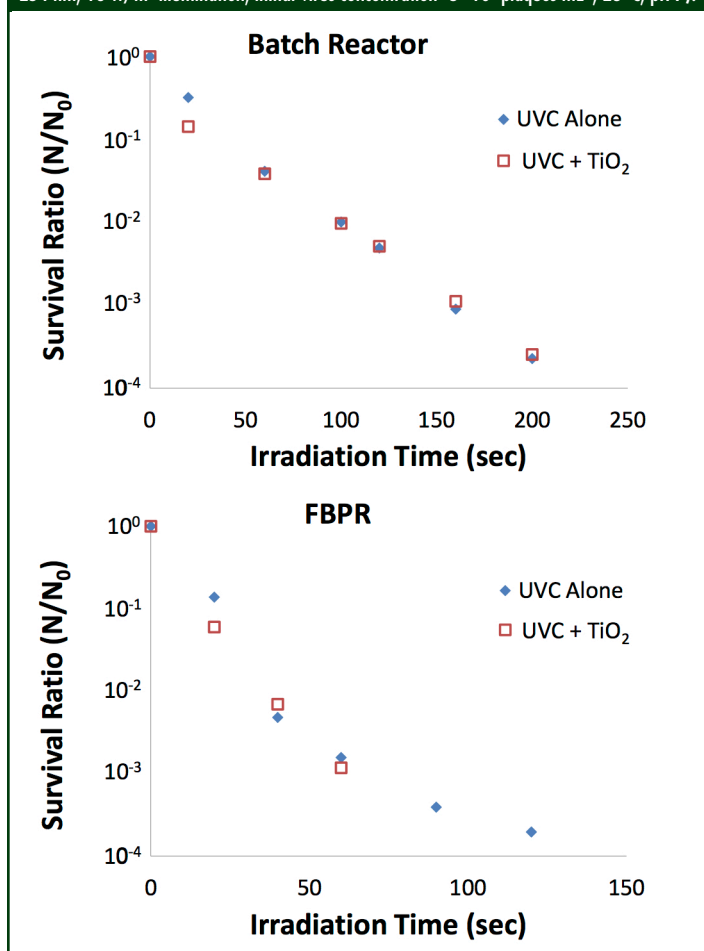
We also tested the ability of the photocatalysts and UV-C light to inactivate adenovirus AV2 in both a batch system and in the FBPR. Photocatalyst material has previously

been shown to be significantly more effective than UV-A light alone to remove viruses from water (Lee et al. 2009). While UV alone is sufficient to remove some viruses, there may be some types of virus that are selectively removed by ROS (Lee et al. 2010). However, the inactivation of AV2 by UV-C was statistically undistinguishable with and without the photocatalyst (Figure 6), indicating that the contact time was again too short to see significant ROS-mediated virus inactivation.

Photocatalytic oxidation has also been shown to be very effective at removing organic contaminants

FIGURE 6

Survival ratio of adenoviruses in a batch reactor (top) and the FBPR (bottom) (0.2 g/L TiO₂, 254 nm, 18 W/m² illumination, initial virus concentration=5×10⁵ plaques mL⁻¹, 23°C, pH 7).



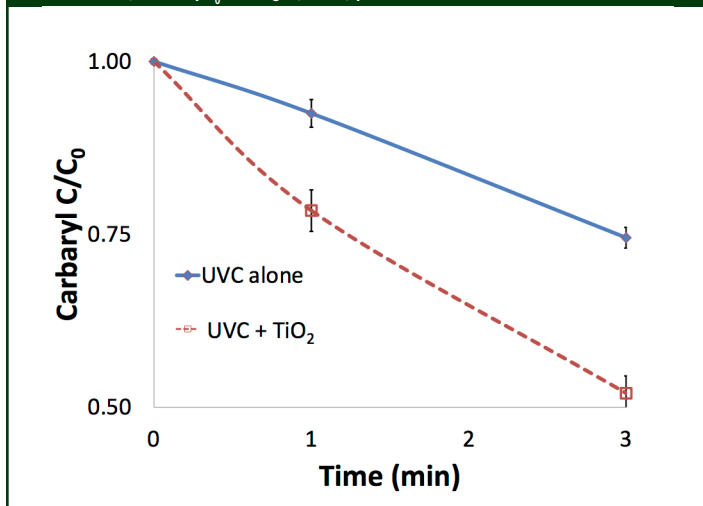
from water (Lee et al. 2011). While pesticides and other priority organic compounds were not analyzed in the local water due to in-country analytical capability constraints, pesticides are commonly used in Swaziland and might be present in these source waters (Swaziland 2010). To test this capability in our system, we used a model pesticide, Carbaryl (1-naphthyl methylcarbamate), which is often used as an insecticide. The photocatalyst was significantly more effective at removing Carbaryl from the water than UV-C alone (Figure 7). The degradation rate of Carbaryl by the photocatalyst plus UV-C light was four times that of UV-C alone (18.9 ± 0.2 vs. 4.7 ± 0.6 min⁻¹ × 10²) after 3 minutes. In the first minute of exposure, indicative of the contact time likely in the field, the photocatalyst/UV-C combination removed almost three times as much Carbaryl as the UV-C light alone. However, in applications such as this

case study, where contact time is limited, these benefits may not be fully realized. The expected contact time for a POU FBPR is approximately one minute, during which time only 25% of the Carbaryl was removed by the photocatalyst/UV system (compared to 8% removal with UV alone). While the partial degradation of priority organics may be an additional benefit of this technology, complete removal of target organics would require higher contact time.

Although the photocatalyst material did not add significantly to water disinfection by UV-C and only partially removed a representative pesticide in this case study, there are many scenarios in which photocatalysis can have an important impact. For example, POU treatment systems that use sunlight illumination would require a very long contact time for disinfection, and photocatalytically-generated ROS could decrease this required treat-

FIGURE 7

Degradation of the pesticide carbaryl in batch reactor under UV light with and without photocatalyst. In the first 60 seconds, which is indicative of the contact time in the field, the PC+UV combo removed 3 times more carbaryl than UV alone (0.2 g/L TiO₂, 254 nm, 18 W/m² illumination, [carbaryl]₀=20 mg/L, 23°C, pH 7).



ment time significantly. One such treatment possibility is to use a reactive liner concept (Figure S2, SI) in which a thin film of water flows in a trough lined with photocatalyst material that is illuminated by sunlight through the water. This design was originally considered for this project, but after assessing local conditions and infrastructure (the water is delivered from the dam to the community garden via underground pipes rather than through open channel flow), it was determined that a fluidized-bed photoreactor (FBPR) would be more suitable for this location.

Implementation Considerations

Before implementation of a POU water treatment system, consideration must be given to safety, cost and any local conditions that could influence the efficacy of the system.

Long Term Tests

Long-term tests were conducted to assess both the potential loss of treatment efficiency over time and the need to replenish the TiO₂ photocatalyst, in addition to determining the potential for long-term release of nanomaterials, which could pose health and safety concerns. While TiO₂ in bulk form is generally considered safe and has been used as an additive in food products for years, proactive safety practices dictate that we mitigate potential or perceived risks by reducing or eliminating the release of

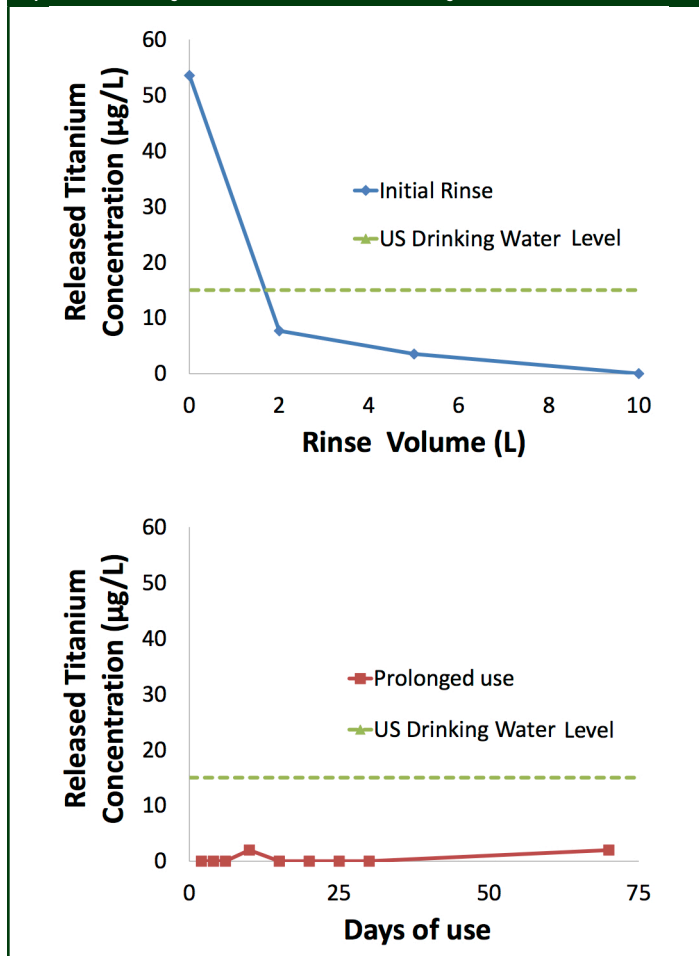
nano-TiO₂ in the effluent (Wiechers and Musee 2010). Therefore, the effluent titanium concentration from the FBPR system was monitored.

There was no loss of ROS production effectiveness (assessed per FFA degradation) over more than two months of daily use (Figure S3, SI). The daily FFA degradation percentage only varied slightly (largest deviation of 3%) from the two-month average. The only maintenance required was an occasional backwash of the system. This suggests that the photoreactor could run for at least two months without a significant loss in efficiency that would require replacement or regeneration of the photocatalyst material.

Figure 8 shows the amount of titanium detected in the effluent of the FBPR. After adding the photocatalyst, the FBPR was rinsed prior to the start of testing. During this rinsing, the effluent titanium concentration -- which is a measure of how much photocatalyst is lost through the filter -- was measured as a function of the rinsing volume. This effluent concentration rapidly decreased from an initial value of 53 µg L⁻¹ to non-detect (ICP-MS limit of detection 1 µg L⁻¹) over the course of 10 liters of rinsing (4 reactor volumes, 10 minutes of operation). By comparison, the TiO₂ concentration inside the reactor is 200 mg L⁻¹, or 4,000 times greater than the maximum effluent concentration during

FIGURE 8

Titanium concentration in the FBPR effluent after addition of photocatalyst, measured by ICP-MS. The x-axes represent the volume of water flushed through the system for the initial rinse (top) and the number of days during the prolonged use test (bottom). The dashed line represents the average bulk Ti concentration in US drinking water.



rinsing. Drinking water in the US contains about 15 µg L⁻¹ of titanium, and the average person consumes 500 µg of bulk titanium per day from water (Weir et al. 2012; WHO 1982), and as much as 50 mg per day of nano TiO₂ per day from food products (Weir et al. 2012). During normal use, the effluent titanium concentration was consistently below detection, with only two samples measuring any titanium (at the lowest detection level-1 µg L⁻¹). Thus, we conclude that there is no significant risk from nanomaterials being released into the effluent water under normal operation.

Cost

Although large water treatment systems generally operate with a lower cost/volume ratio, the capital investment cost is often prohibitive for small-scale applications or rural/

underdeveloped areas. Additionally, large scale systems require more upkeep, operation and maintenance expertise, all of which are prohibitive for this situation. A POU treatment system is more applicable for this and many similar sites given the small flow-rate and low capital cost requirement. POU systems are generally more economical when serving a small population, or when differential treatment -- where the intended use dictates different levels of treatment -- is required (Qu et al. 2012).

Table 3 summarizes cost information for some disinfected/POU treated water options that could be used at this site. At this small scale UV disinfection (using UV-C, bactericidal lamps) is significantly less expensive than most other POU treatment options. This low cost does not include primary treatment, such as filtration or sedimentation,

which may be required depending on the turbidity of the source water. Commercial UV disinfection systems for the capacity necessary in the Swaziland community irrigation systems cost from \$3,000 to \$10,000. The operational cost of the FBPR treatment system discussed above is very similar to a standard UV disinfection system (~\$2 per 1,000L based on production and operation costs for this unit). Both this device and other commercial UV treatment systems require a power source, which could be supplied by a car battery, solar panel, or in some cases by connection to a local power grid. The design and manufacture cost of the prototype bench-top FBPR used in this study was less than \$5,000. The cost to manufacture a field-scale FBPR would be very similar since the design work is already accomplished, making it competitive with commercially available systems.

Local Conditions

Turbidity has the potential to block light and hinder the efficiency of FBPR systems. Several of the sites in Swaziland had turbidity levels > 200 NTU (Table 1). In order to test the effect of turbidity on ROS generation (assessed per FFA removal), we ran batch reactors exposed to various turbidity levels. Turbidity was introduced through the addition of bentonite clay, which is similar to the type of clay found in Swaziland surface water. Turbidity had little effect on FFA degradation up to 100 NTU (Figure S4, SI). For treatment at locations with turbidity levels below 100 NTU, no pretreatment of the water will be required. However, for treatments at locations with higher turbidity levels, some form of pretreatment (sedimentation, filtration, coagulation/flocculation, etc.) will need to be employed to avoid loss of efficiency due to light occlusion.

Because the FBPR requires power to operate the light source, and most of the locations of the earthen dams are removed from power grids, the FBPR system will require a small power supply. While the power requirement could easily be generated with a small solar panel, the risk of theft for a solar panel is quite high. A simple car battery could power the device for several weeks, requiring occasional recharging. One technician could maintain a large number

of systems, including periodic replacement of bulbs and photocatalyst and recharging of the power supply with very minimal training.

Conclusions and Recommendations

A nano-photocatalyst fluidized bed photoreactor system that is capable of removing biological contamination down to acceptable regulatory levels within a reasonable contact time was successfully designed and tested. This system is also capable of removing Carbaryl as a representative persistent organic pollutant at a higher rate than commercially available UV treatment systems, although complete removal requires longer contact time. This added functionality towards pesticides combined with the similar cost compared to commercial system could make the FBPR a promising technology option for POU applications such as the irrigation water in Swaziland. Prior to field-scale testing, however, further work is required to decrease the photocatalytic contact time necessary for complete degradation of organic pollutants and increased disinfection/virus removal compared to current UV disinfection technologies (e.g., improve contaminant selectivity by enabling sorption close to ROS generating sites, or increase photocatalytic ROS production). Nano-enhanced, point-of-use water treatment technologies have great potential to decrease the occurrence of devastating water-borne illnesses in many developing areas of the world. Further studies to enable implementation of these technologies will be needed to realize the expected benefits in protecting human health and enabling safer irrigation.

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