Q-440

Photocatalytic Inactivation of Viruses Using Low-Pressure Ultraviolet Light in a Titanium Dioxide Suspension

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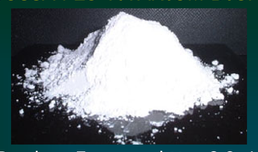
Abstract

The carcinogenic potential of chlorine disinfection byproducts and recent changes in water quality regulations have led to a greater emphasis on alternative disinfection mechanisms. Although the inactivation of viruses using low-pressure ultraviolet (UV) light has been studied extensively, little research has been performed to demonstrate the efficacy of using UV light in conjunction with a photocatalyst for viral inactivation. The intent of this research is to explore the synergistic disinfection potential of ultraviolet light and titanium dioxide (TiO_2) with respect to four potential surrogate bacteriophages (MS2, PRD1, phi-X174, and fr) and adenovirus type 4. Although adenoviruses are highly resistant to UV disinfection, the reactive oxygen species generated by TiO_2 may provide a greater level of inactivation when added to typical UV reactors. A bench-scale collimated beam apparatus comprised of a 15-watt, low-pressure (254 nm) UV bulb and 1 mg/L Degussa P25 TiO_2 was used in each experiment. This setup achieved nearly 20% reductions in the UV doses required for four-log inactivation of the UV-resistant viruses (MS2, PRD1, and adenovirus 4). In addition to the standard setup, these dose reductions were achieved by changes in pH based on isoelectric points and pre-exposure of the TiO_2 nanoparticles to UV light. For the UV-susceptible bacteriophages (fr and phi-X174), the UV dose reductions ranged from 0-10%, respectively. In addition, this study demonstrated the application of an integrated cell culture quantitative polymerase chain reaction (ICC-qPCR) method for adenovirus disinfection studies. Using the primary liver carcinoma (PLC) cell line and a 24-hour incubation period, the ICC-qPCR method provided significant differentiation between standard spiking levels in addition to a negative control. Furthermore, the incubation period produced a 10-fold increase in viral quantity over the standard spiking levels. These results provide a proof-of-concept for the synergistic effects of UV light and TiO_2 in addition to substantiating further testing of adenovirus and other potential pathogens in water treatment applications.

Background

DEGUSSA P25 TITANIUM DIOXIDE



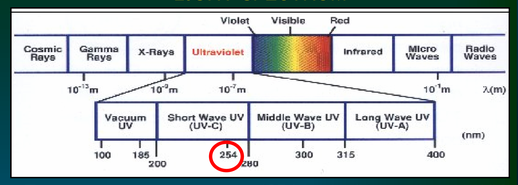
Bandgap Energy = hν = 3.2 eV

Activation Wavelength = λ < 387 nm

Optimal Dose = 1 mg/L

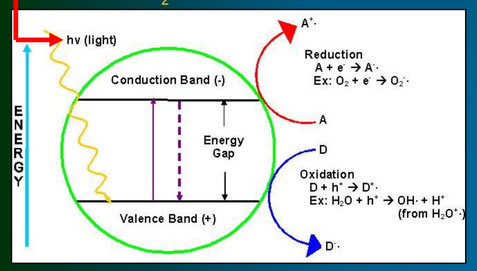
Sonication = 200 W/L for 15 minutes

LIGHT SPECTRUM

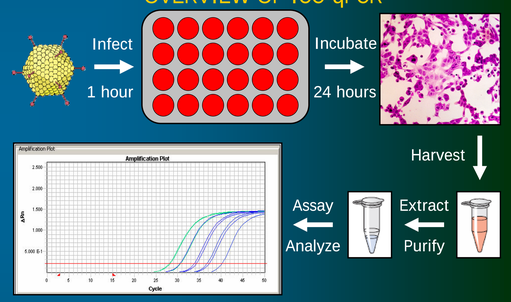


The monochromatic output (254 nm) of low-pressure UV bulbs is the most effective wavelength for disinfection purposes. Conversely, medium-pressure UV bulbs emit light over a wide range of wavelengths but at much higher intensities. Black-light bulbs (350-400 nm), which have been used in similar photocatalysis studies, are capable of activating TiO_2, but they are not sufficient for disinfection in water and wastewater treatment.

TiO_2 PHOTOCATALYSIS

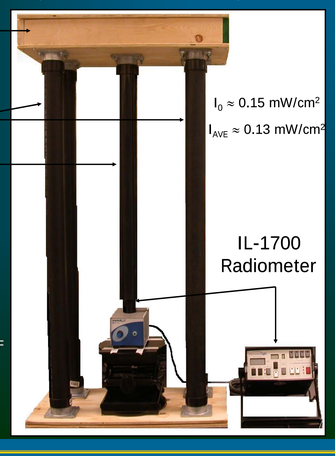


OVERVIEW OF ICC-qPCR



COLLIMATED BEAM DESIGN

The purpose of a collimated beam is to form parallel rays of light that strike the target surface at a right angle, thereby standardizing each irradiation experiment.



Correction Factors:

Petri = 0.890
Reflection = 0.975
Divergence = 0.984
Water = 0.995

Intensity Calculation:

$I_{AVE} = I_0 \times PF \times RF \times DF \times WF$
Unit = mW/cm²

Dose Calculation:

Dose = I_{AVE} x Time
Unit = mW-s/cm² = mJ/cm²

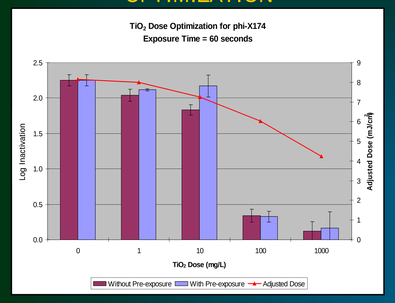
VIRUSES

Adenoviruses are highly resistant to UV inactivation. Four-log inactivation may require a UV dose of up to 200 mJ/cm². Using optimized TiO_2 parameters from previous bacteriophage experiments, photocatalysis may be able to reduce the dose requirements for adenovirus inactivation. The objective of this study was to quantify the UV and photocatalytic inactivation of adenovirus type 4 using an ICC-qPCR approach.

Double-stranded DNA	Double-stranded DNA	Single-stranded RNA	Single-stranded RNA	Single-stranded DNA
Adenovirus 4	PRD1	MS2	fr	phi-X174
PLC/PRF/5	*Salmonella typhimurium*	*E. coli* 15597	*E. coli* 19853	*E. coli* 13706
[CRL-8024]	(LT2) [19585]			
pH_{zpc} = ?	pH_{zpc} = 3.6	pH_{zpc} = 3.7	pH_{zpc} = 9.0	pH_{zpc} = 6.6

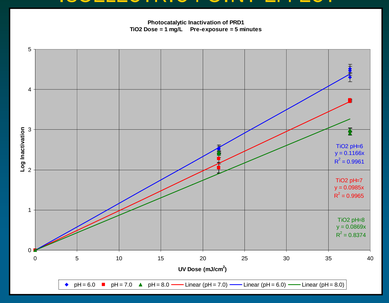
Results

TiO_2 DOSE OPTIMIZATION



As the TiO_2 dose increases, the water becomes increasingly cloudy—approaching the color of milk—and inactivation decreases significantly. As a result, 1 mg/L was selected as the optimal dose to minimize light scattering and reflection.

pH OPTIMIZATION & ISOELECTRIC POINT EFFECT



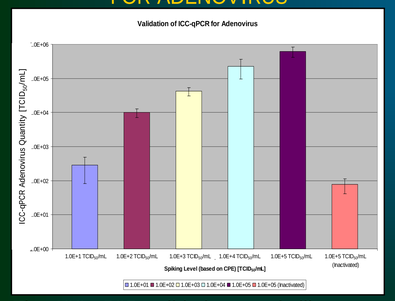
The isoelectric point of TiO_2 is approximately 6.3. At a pH of 6.0, positively charged TiO_2 will be attracted to the negatively charged bacteriophages, thereby increasing the exposure of the bacteriophages to surface hydroxyl radicals.

DOSE REQUIREMENTS FOR 4-LOG INACTIVATION (mJ/cm²)

Bacteriophage	UV	UV/TiO_2	% Reduction
MS2	46	39	15%
PRD1	41	34	17%
phi-X174	16	15	6%
fr	15	15	0%

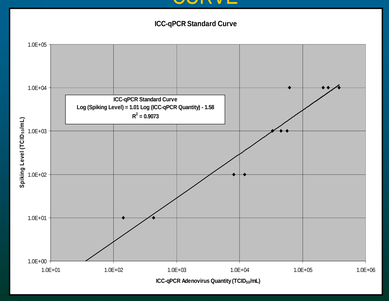
The dose requirements and percent reductions are based on the optimized TiO_2 conditions: 1 mg/L of Degussa P25 TiO_2, pre-exposure of the TiO_2 nanoparticles to UV light, and pH adjustments based on isoelectric points.

ICC-qPCR VALIDATION FOR ADENOVIRUS



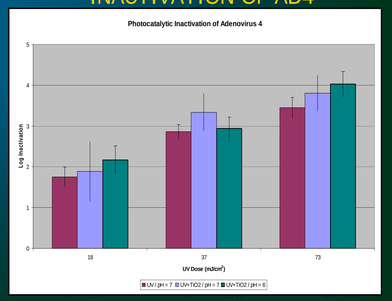
The ICC-qPCR validation graph illustrates the differences between the infectious spiking levels and the inactivation control.

ICC-qPCR STANDARD CURVE



The ICC-qPCR standard curve can be used to calculate the original number of infectious adenoviruses in unknown samples.

PHOTOCATALYTIC INACTIVATION OF AD4



This graph illustrates the differences between the UV and UV/TiO_2 samples after calculating inactivation using the ICC-qPCR method.

Summary

- Due to light scattering, reflection, and absorbance at higher TiO_2 doses, 1 mg/L was selected as the optimal dose.
- pH adjustments based on isoelectric points increased the photocatalytic efficiency for some bacteriophages.
- Photocatalytic inactivation was more effective against the UV-resistant bacteriophages (MS2 and PRD1) than the UV-susceptible bacteriophages (phi-X174 and fr).
- TiO_2 photocatalysis does not seem to significantly improve adenovirus inactivation.
- Although the destruction of organics will likely drive the use of TiO_2 photocatalysis, this technology will also provide some level of microbial inactivation. More research is necessary to maximize the effectiveness of this technology and generate a better understanding of potential applications.

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