Photocatalytic Microfluidic Reactors Utilizing Titania Nanotubes on Titanium Mesh for Degradation of Organic and Biological Contaminants

Harikrishnan Jayamohan^a, York R. Smith^{b,*}, Bruce K. Gale^a, Swomitra K. Mohanty^c, Manoranjan Misra^b

^a*Department of Mechanical Engineering, University of Utah, Salt Lake City, Utah, 84112, USA*

^b*Department of Metallurgical Engineering, University of Utah, Salt Lake City, Utah, 84112, USA*

^c*Department of Chemical Engineering, University of Utah, Salt Lake City, Utah, 84112, USA*

Abstract

Microfluidic reactors have gained considerable interest for photocatalytic degradation of contaminants in water. These systems have advantages such as large surface-area-to-volume ratio and high control of fluid flow, yet still suffer from drawbacks due to limited mass transport associated with laminar flow. The use of titania nanotubes synthesized on a mesh substrate show improved photocatalytic performance in comparison to nanotubes synthesized on a foil substrate in a microreactor. At the lowest flow rate (25 $\mu\text{L}/\text{min}$), the area normalized fractional conversion of methylene blue increased from 20% for foil to 46% in the case of nanotubes on mesh. The enhanced photocatalytic performance of the mesh is due to shorter diffusion distance and induction of flow perturbation. Also, the radially outward oriented nanotubes formed over the circumference of the titanium wire leads to the efficient capture of both reflected and refracted light. The device was also applied for inactivation of *E. coli* O157:H7. At a flow rate of 50 $\mu\text{L}/\text{min}$, the titania nanotubes on a mesh microreactor was able to achieve >99% inactivation of *E. coli* under AM 1.5 ($\approx 100 \text{ mW}/\text{cm}^2$) simulated solar light.

*Corresponding author

Email address: york.smith@utah.edu (York R. Smith)

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inactivation

1. Introduction

According to estimates, 1.2 billion people lack access to safe drinking water, which contributes to the death of 3900 children daily[1]. Hence, access to clean water is a worldwide concern. In both industrialized and developing nations, chemical and biological contaminants are finding their way into water bodies due to increasing human activity [1]. Cleanup and reuse of polluted wastewater is an attractive solution to some of these issues. Low-cost and high-efficiency water remediation technologies are needed to achieve the same [2]. Conventional wastewater treatment technologies such as adsorption or coagulation merely concentrate the pollutants present by transferring them to other phases [2]. Other conventional methods such as sedimentation, filtration, chemical, and membrane technologies are expensive and potentially generate toxic secondary pollutants [1].

Advanced Oxidation Processes (AOP) could solve some of the issues associated with conventional water treatment methods. These processes work by the generation of transitory highly reactive oxygen species (ROS) for mineralization of chemical and biological pollutants present in water [2]. Among these AOPs, photocatalytic environmental remediation employing semiconductor photocatalysts has been widely applied for water-based pollutants [3, 2]. Nanomaterial semiconductor photocatalysts have been used due to their interesting properties over bulk materials. Many studies have used powdered photocatalysts suspended in solution [4, 5]. However, the use of powdered photocatalysts necessitates their downstream recovery. This can lead to increased operational and capital costs [5, 6]. Also, the use of powdered catalyst particles limit the depth of penetration of light due to strong adsorption and scattering [7, 8]. The immobilization or growth of photocatalysts as a film on a substrate eliminates many of these drawbacks [6].

Microfluidic reactors (microreactors) have been increasingly applied to water remediation over conventional macroscale reactors [9, 10]. This is because conventional macroscale reactors have limitations due to mass transport and poor photon management [5]. In the case of microreactors, the thin layer of liquid over the catalyst ensures lesser photons are lost due to scattering [11]. Microreactors can be advantages over conventional macroscale reactors due to large surface to volume ratio, smaller diffusion distance, and large mass transfer efficiency[12]. Microfluidic photocatalytic reactors have been reported to have higher photocatalytic efficiency compared to conventional reactors [10]. Current microfluidic formats face a major drawback due to limited mass-transport associated with laminar flow[5]. To overcome this limitation, Li et al. reported the use of a fiberglass coated with P25 titanium dioxide nanoparticle (TNP) layer for the degradation of methylene blue (MB)[5]. The new design, incorporating the same catalyst (TNP), but on a geometrically different substrate (fiber) yielded higher degradation over a conventional microreactor platform involving P25 TNP layer embedded on a flat surface.

Titanium dioxide (TiO_2) has been widely applied to photocatalytic degradation of chemical and biological pollutants[13, 6, 14, 15]. Titania nanotube arrays (TNA) are of particular interest due to their simple synthesis and improved ability to transport photogenerated charges as compared to their TNP counterpart[16]. Titania nanotube arrays have shown to have enhanced photocatalytic properties compared to TNP layers in a macroscale batch reactor configuration[17]. Further, by electrochemical anodization, TNA can be synthesized on different titanium (Ti) metal substrates, having varied geometries (e.g., thin wires[8], meshes[16], and curved surfaces[18]).

TiO_2 based catalysts in the form of TNA[11] and TNP[19, 10, 5] have been applied in microreactors for photocatalytic degradation. We recently reported the application of TNA synthesized on a foil (TNA_{foil}) for degradation of MB in a microreactor[11]. The TNA_{foil} had enhanced photocatalytic performance over P25 TNP layer when used in a microfluidic format.

Although TNA_{foil} has shown promising results for photocatalytic applica-

tions, the use of metal foils has limitations (such as the opacity, inefficient use of Ti, and reduced flexibility). As an alternative, metal meshes provide an approach that allows for high flexibility, efficient Ti utilization, and transparency. Such a format has shown to be effective in applications such as dye-sensitized solar cells[20].

We report the use of TNA grown on a Ti mesh (TNA_{mesh}) for photocatalytic degradation of MB and inactivation of *E. coli* O157:H7 in a microfluidic format. The microfluidic device was fabricated using non-cleanroom based technique which makes it suitable for large scale applications[21]. The degradation performance is compared to that of previously reported data using TNA_{foil} at different flow rates in a geometrically similar microreactor[11]. We also report the use of TNA_{mesh} for the photocatalytic inactivation of *E. coli*. TiO_2 based photocatalysts have been shown to have bactericidal and bacterial endotoxin decomposing capability[22, 23, 24, 14]. The use of TNA for inactivation of pathogens in a flow through system has yet to be fully explored.

2. Experimental

2.1. Preparation and characterization of TNA on foil and mesh

Titania nanotube arrays grown on a titanium mesh were synthesized by electrochemical anodization similar to an earlier reported protocol [16]. In short, Ti gauze (50 mesh woven from 0.102 mm diameter wire, 64% open area) was obtained from Alfa Aesar and cut into 3 x 2 cm² dimensions. The Ti gauze was first washed with isopropanol and DI water under sonication for 10 mins each, and then electropolished in 1 °C glacial acetic acid/perchloric acid (9:1 volume ratio) at 60 V under sonication for 1 min [25]. The electrochemical anodization was carried out at an applied potential of 60 V (D.C.)(Agilent, E3647A) for 60 minutes. The thus formed TNA_{mesh} was rinsed with DI water, air dried and subsequently annealed in an atmosphere of N_2 +2% H_2 at 500 °C (1.6 °C/min ramp rate) for 2 h. The morphology of the thus formed TNA_{mesh} film was characterized using a field emission scanning electron microscope (SEM) (Hitachi,

88 S-4800).

89 2.2. Fabrication of microfluidic channel and integration of TNA_{mesh} substrate

90 The microfluidic device was fabricated by soft lithography [21] similar to that
91 reported in our earlier study[11]. In short, the mold was cut on a tape using
92 a laser. Next, a polydimethylsiloxane (PDMS) mixture was poured onto the
93 mold, and cured in an oven to create the PDMS layer. Subsequently, inlet and
94 outlet channels were bored onto the PDMS channel and the TNA_{mesh} catalyst
95 was embedded into the PDMS channel. Finally, a corona activated glass slide
96 was bonded to the PDMS layer. A photograph of the microfluidic reactor is
97 provided in the Supporting information (Fig. S1).

98 2.3. Evaluation of the photocatalytic degradation of methylene blue

99 The photocatalytic degradation of the device was evaluated using MB as a
100 model pollutant. MB is a non-biodegradable dye and is used for characteriz-
101 ing photocatalytic performance [26, 27, 17]. The experimental setup used to
102 evaluate the photocatalytic performance of the device is depicted in our earlier
103 work[11]. In a typical experimental run, 5 ml of 18 mM aqueous solution of MB
104 was injected through the inlet into the microfluidic device using a syringe pump
105 (KD Scientific, Manassas, VA) via Tygon tubing (0.02 inch/0.0508 mm inner
106 diameter) at different flow rates ranging from 25-200 $\mu\text{L}/\text{min}$. The microfluidic
107 device was irradiated with AM 1.5 simulated solar light ($\approx 100 \text{ mW}/\text{cm}^2$). The
108 intensity of the light was measured at the surface of the microfluidic device using
109 a handheld power meter (Nova, Ophir-Spiricon, UT). The degraded MB solution
110 was collected and the concentration was determined by monitoring the change in
111 characteristic absorption peak at $\lambda = 664 \text{ nm}$ using a UV-vis spectrophotometer
112 (Shimadzu Corp., Japan). The fractional conversion was calculated by:

$$X(\%) = \frac{A_0 - A}{A_0} 100 \quad (1)$$

113 where A_0 is the initial concentration absorbance value, and A is the ab-
114 sorbance value of the degraded solution. The experiment was repeated in the

115 absence of AM 1.5 light to evaluate the amount of MB adsorbed on the cat-
 116 alyst. The fractional conversion was normalized with respect to the substrate
 117 area exposed to normal incident light[8]. The results were compared to normal-
 118 ized fractional conversion of MB using a TNA_{foil} (12 μm and 7 μm nanotube
 119 lengths) reported in our earlier work[11].

120 2.4. Evaluation of the photocatalytic inactivation of *E. coli*

121 The photocatalytic inactivation of *E. coli* was evaluated using TNA_{mesh} in a
 122 microreactor as described above. *E. coli* O157:H7 (non-pathogenic strain, Cat-
 123 alog no. 700728, ATCC) was used to prepare different concentrations (1000 and
 124 10000 CFUs/mL) of *E. coli* in 1X PBS solution [28]. The concentration range
 125 of *E. coli* was chosen based on total coliform levels in municipal wastewater[29].
 126 The experimental setup is the same as that for MB degradation mentioned pre-
 127 viously. A 4 mL sample of the *E. coli* solution was taken in a syringe, 3 mL of
 128 which was injected using a syringe pump through the inlet into the microfluidic
 129 device. The flow rates were varied from 25-200 $\mu\text{L}/\text{min}$ in the absence and pres-
 130 ence of AM 1.5 simulated solar light ($\approx 100 \text{ mW}/\text{cm}^2$). The intensity of the light
 131 was varied from 10-100 mW/cm^2 to evaluate the effect on inactivation. The in-
 132 activated *E. coli* solution was collected and plated on agar (Difco Nutrient Agar,
 133 Catalog no. 213000, Becton Dickinson, Sparks, MD), incubated at 37°C for 12
 134 hours and subsequently counted to calculate the final concentration (C_f). The
 135 1 mL stock solution left in the syringe was also plated after the experimental
 136 run (to avoid any non-photocatalytic, room temperature based inactivation of
 137 *E. coli* during the experimental run) to determine the initial concentration (C_0).
 138 The survival ratio (S.R) was calculated by:

$$S.R(\%) = \frac{C_f}{C_0} 100 \quad (2)$$

139 where C_f is the final concentration (CFU/mL) of *E. coli* post inactivation
 140 in the microfluidic device, and C_0 is the initial concentration (CFU/mL) of *E.*
 141 *coli* (solution left in the syringe). The experiment was repeated in the absence
 142 of AM 1.5 light to evaluate the amount of *E. coli* adsorbed/trapped in the

Figure 1: SEM images of TNA_{mesh} anodized at 60 V for 1 hour, showing the (a) low-magnified overall image of nanotubes on the anodized mesh, (b) sidewall, and (c) top morphology.

143 catalyst. The experiment was also performed in the presence of AM 1.5 light in
 144 the microreactor without the catalyst embedded in it to evaluate the effect of
 145 light inactivation only on *E. coli*.

146 3. Results and discussion

147 3.1. Properties of Titania nanotubes

148 The morphology of the TNA_{mesh} was characterized by SEM. Fig. 1 shows
 149 the SEM images of the annealed TNA_{mesh} . From Fig. 1a, fissures and bundling
 150 of nanotubes are observed in TNA_{mesh} (unlike TNA formed on a planer substrate/ TNA_{foil}).

These are due to the curvature-induced stress during the formation of nanotubes and the outward radial growth of the nanotubes on a curved Ti substrate[8, 20]. Such a morphology is observed in TNA formed on wire-type substrates[30]. The TNA_{mesh} nanotube length is approximately 8 μm (1 hour anodization). The TNA_{mesh} tubes have an approximate inner diameter of 80 nm and wall thickness in the range 10-15 nm. Though the orientation of nanotubes differ, the morphology (nanotube height and diameter) of the TNA_{mesh} is similar to the TNA_{foil}[11].

3.2. Normalized degradation efficiency (MB) of the microfluidic reactor- Effect of flow rates

The results of the degradation at different flow rates over TNA_{mesh} (8 μm) vs. TNA_{foil} (12 μm and 7 μm) with AM 1.5 irradiation are presented in Fig. 2. It is evident that the normalized fractional conversion using TNA_{mesh} is higher than TNA_{foil}, in the flow range under consideration (25-200 $\mu\text{L}/\text{min}$). Both the TNA_{mesh} and TNA_{foil} catalysts show similar trends in a decrease in degradation in the 25-50 $\mu\text{L}/\text{min}$ domain. This is intuitive since an increase in flow rate would result in less time for the MB to diffuse and come in contact with the catalyst surface. However, it is interesting to note that the degradation performance of both the TNA_{mesh} and TNA_{foil} catalysts remain constant over the 50-200 $\mu\text{L}/\text{min}$ domain. Such a trend has been previously observed, and is primarily due to the faster generation of oxidizing species with increased flow rate[11].

The TNA_{mesh} (8 μm tube length) shows a higher normalized fractional conversion (NFC) compared to TNA_{foil} in the flow domain under consideration. At the lowest flow rate (25 $\mu\text{L}/\text{min}$), TNA_{mesh} exhibits a NFC more than twice (2.5 times) that of TNA_{foil} of comparable length (7 μm). Similarly at the highest flow rate (200 $\mu\text{L}/\text{min}$), TNA_{mesh} has a NFC 2.4 times higher than TNA_{foil} (7 μm). Even in the case of longer tube geometry, TNA_{foil} (12 μm tube length) has lower NFC than TNA_{mesh}. This is in spite of the fact that nanotube length on TNA_{mesh} is 66% lower than that on TNA_{foil}. The length

Figure 2: Effect of flow rate on MB degradation for TNA_{mesh} and TNA_{foil} catalyst in the presence of AM 1.5 light. The fractional conversion is normalized with respect to substrate area exposed to normal incident light. The data associated with 7 and 12 μm is from ref.[11].

Figure 3: Effect of flow rate on *E. coli* inactivation for TNA_{mesh} (8 μm length) in the presence and absence of AM 1.5 light (1000 CFU/mL starting concentration).

181 of the nanotubes is reported to have an effect on the fractional conversion of
 182 MB in microfluidic reactors[11].

183 3.3. Inactivation (*E. coli*)- Effect of flow rates

184 The results of the inactivation of *E. coli* at different flow rates over TNA_{mesh}
 185 are presented in Fig. 3 and Fig. 4. In the absence of AM 1.5 light, it is evident
 186 that in the given flow range (50-200 $\mu\text{L}/\text{min}$) there is little inactivation (S.R
 187 84-99.5%) of *E. coli* due to adsorption by the catalyst. Also, at the lowest
 188 flow rate (50 $\mu\text{L}/\text{min}$), there is little inactivation (S.R >92 %) of *E. coli* under
 189 visible light illumination in the absence of TNA_{mesh} catalyst (not shown). This
 190 indicates that the inactivation is primarily due to photocatalytic generation of
 191 ROS species by TiO_2 and not due to the inactivation by the UV component of
 192 light. This has been previously established for batch reactor systems applied to
 193 *E. coli* inactivation[31, 32].

194 For a 1000 CFUs/mL starting concentration, at the lowest flow rate (50
 195 $\mu\text{L}/\text{min}$), almost 100% of the *E. coli* is inactivated using the TNA_{mesh} catalyst.

Figure 4: Effect of flow rate on *E. coli* inactivation at different starting concentration for TNA_{mesh} in the presence of AM 1.5 light.

Even, at the highest flow rate more than 92% of *E. coli* is inactivated. As the starting concentration increases by a order of magnitude, the S.R increases from <1% to 6% (Fig. 4). Although, the principle of photocatalytic degradation of both MB and *E. coli* are similar viz. by degradation by ROS, the actual rate of degradation will be different due to differences in diffusion coefficient between the two. In addition, *E. coli* is a straight rod shaped organism ($\approx 0.5 \mu m$ in width by $2 \mu m$ in length), consisting of complex structures of lipopolysaccharide, a peptidoglycan cell wall, and lipid bilayers of inner and outer membranes, etc[33].

Due to the complex nature of photocatalytic inactivation of microbes, often times empirical expressions are used to describe the overall kinetics. One of the most commonly used models for photocatalytic inactivation of microbes is the Chick-Watson model[34, 35]. A modified Chick-Watson model[36, 37](Eqn. 3) was used to describe the overall kinetics with respect to residence time (τ) for *E. coli* concentrations of 1000 and 10000 CFU/mL. The model was fit with the experimental data using a non-linear fitting routine (OriginPro[®]):

Figure 5: Kinetics with respect to residence time (τ) for *E. coli* concentrations of 1000 and 10000 CFU/mL.

$$\log \frac{C_t}{C_0} = k_1 [1 - e^{-k_2 \tau}] \quad (3)$$

where C_t is the *E. coli* concentration (CFU/ml) at time t . The modified Chick-Watson model was found to have good agreement with the experimental data (Fig. 5). The parameters, k_1 and k_2 for 1000 CFU/mL were found to be -2.23 ± 0.132 and $0.544 \pm 0.083 \text{ min}^{-1}$, respectively, with an adjust R^2 value of 0.96993 and $\chi^2 = 0.00754$. For 10000 CFU/mL *E. coli* concentration, the parameters k_1 and k_2 were found to be -0.8794 ± 0.0747 and $0.1966 \pm 0.0343 \text{ min}^{-1}$, respectively, with an adjust R^2 value of 0.9794 and $\chi^2 = 0.00121$.

Figure 6: Effect of light intensity on *E. coli* degradation for TNA_{mesh} (1000 CFU/mL starting concentration, 100 μ L/min flow rate).

218 3.4. Inactivation efficiency of *E. coli*- Effect of light intensity

219 With a decrease in light intensity, there is commensurate drop in *E. coli*
 220 inactivation. A 50% decrease in light intensity (50 mW/cm²) results in a 50%
 221 drop in inactivation. From the Fig. 6, there appears to be a linear relationship
 222 between inactivation rate and light intensity. This indicates the process is re-
 223 action dominated[38], i.e. the process has not reached a limiting light intensity
 224 where the electron-hole pair recombination limits a further increase in inactiva-
 225 tion. This means by further increasing the light intensity, the inactivation rate
 226 can be increased or a higher flow rate/process throughput can be achieved (at
 227 a given inactivation rate) till a certain limiting point[38]. This could be due to
 228 the low light scattering observed in the case of TNA_{mesh} format.

229 3.5. Discussion

230 The mechanism of photocatalytic MB degradation is well reported in litera-
 231 ture [3, 17]. The MB dye molecules adsorbed on the surface of the catalyst are
 232 oxidized by the photoinduced holes generated by the TiO₂ catalyst to form a
 233 radical $\bullet$ MB⁺. These radicals further react with O₂ to form [MBOO $\bullet$]⁺. Subse-

Figure 7: TNA_{foil} and TNA_{mesh} catalyst layouts in the microfluidic channel illustrating the shorter diffusion path using a mesh substrate.

quently the heteropolyaromatic ring is broken, and degradation occurs [39]. It is important to mention that previous investigations have studied the visible light activity of TNA[40, 41]. The visible light activity of TNA can be attributed to doped carbon sourced from ethylene glycol in the anodization bath[42, 41].

Titania nanotubes formed on titanium wires have been reported to demonstrate higher dye degradation performance in comparison to TNA_{foil} using a conventional macroscale batch reactor[8]. The higher degradation of the former was attributed to the geometry wherein the wires are juxtaposed next to one another. Also, on a wire or mesh substrates, titania nanotubes grow radially outwards in a uniform and compact manner. Such a configuration, enables them to not only to utilize the absorbed light, but also the reflected and refracted light as well[8]. In the case of a microfluidic format, the enhanced photocatalytic degradation of MB using the TNA_{mesh} catalyst can be attributed to a shorter mass transport length[5]. Unlike in the case of TNA_{foil} , the TNA_{mesh} catalyst remains suspended across height of the channel (Fig. 7). Hence, the MB molecules do not have to diffuse all the way to bottom of the microfluidic channel to reach the catalyst surface. The differences in the substrate geometry enable better access of the pollutant molecules to the catalyst surface. This principle

Figure 8: Degradation scheme of *E. coli*/MB by ROS generated by TNA catalyst. The lifetime of ROS like $\text{OH}^\bullet$, $\text{O}_2^{\bullet-}$, $\text{HOO}^\bullet$ is short and can only degrade pollutants at surface of the catalyst. H_2O_2 molecules are more stable and diffuse from the catalyst surface to pollutants present in the bulk solution [31].

has been utilized in earlier studies, immobilizing TNP catalyst on fiberglass (as compared to a planar surface) to enhance mass transport[5]. Thus the mass transport is enhanced in the case of TNA_{mesh} in comparison to TNA_{foil} . This is especially critical in microfluidic formats wherein the mass transport is limited due to the laminar nature of the flow. Another reason for the enhanced performance can be attributed to the flow perturbation induced by the mesh[5]. In our previous work on degradation of MB using TNA_{foil} in microreactors, we show that the diffusion has a higher effect on fractional conversion than rate constant[11]. Since the use of TNA_{mesh} results in an enhanced diffusivity (shorter mass transport length), the enhanced fractional conversion of MB by TNA_{mesh} over TNA_{foil} can also be attributed to the same.

The application of TiO_2 photocatalysts for *E. coli* inactivation was first reported by Yoshihiko et al.[31]. The mechanism of degradation of bacteria is similar to that for MB viz. due to the generation of ROS ($\text{OH}^\bullet$, O_2^- , $\text{HOO}^\bullet$, H_2O_2) by TNA[43, 33]. The photo generated hole sites in the valance band of titania reacts with water to form hydroxyl radicals ($\text{OH}^\bullet$), while the electrons promoted to the conduction band react with molecular oxygen to form superoxide ions and H_2O_2 . These further react with water to form additional hydroxyl radicals (Fig. 8). An alternative mechanism, involving the direct oxidation of bacteria through the photogenerated holes has been ruled out[23]. The photogenerated radicals are responsible for the inactivation of bacteria, by oxidizing organic material up to complete mineralization[23, 14]. The generated radicals attack the bacterial cell wall, leading to cell wall rupture[22, 23]. This cause the degradation of lipopolysaccharide, a cell wall constituent and promote peroxidation of the lipid membrane[24, 44]. This results in the increase in the permeability of cells, the leakage of intracellular molecules, penetration of ROS into the cytoplasmic inner membrane, and finally induces bacterial cell death[32]. The inactivation of the bacteria could generate pyrogenic and toxic ingredients such as endotoxins. Endotoxins are the lipopolysaccharide cell wall constituents of Gram-negative bacteria like *E. coli*. But TiO_2 based photocatalysis have shown to have deactivating effect on endotoxins[24]. The quantification of the de-

283 activating effect of TNA based photocatalysts on endotoxins in a microfluidic
 284 reactor will be the subject of future work. The use of microfluidic photocatalytic
 285 systems involving TNA_{mesh} could be used to harvest clean and inexpensive en-
 286 ergy from the sun for photocatalytic water remediation. While high-throughput
 287 applications can be a challenge due to lower volume of solutions involved with
 288 microreactors, they can be resolved by scaling up the microreactors[45]. These
 289 could also be used as portable water treatment devices especially in developing
 290 countries. The technique could be also be used in conjunction with current ul-
 291 traviolet purifiers, wherein the power consumption can be significantly reduced,
 292 or the time for effective water treatment can be significantly reduced.

293 4. Conclusion

294 The photocatalytic degradation performance using TNA_{mesh} and TNA_{foil}
 295 catalyst in a microreactor was compared at different flow rates under simulated
 296 AM 1.5 light. The experimental results show that, TNA_{mesh} exhibited enhanced
 297 degradation (area normalized) of MB pollutant in comparison TNA_{foil}. The
 298 enhanced performance of TNA_{mesh} over TNA_{foil} is due to shorter diffusion
 299 distance and induction of flow perturbation, along with the efficient capture of
 300 both reflected and refracted light in the case of former. The morphology of the
 301 individual nanotubes on both the TNA_{mesh} and TNA_{foil} substrate is similar.
 302 It is the orientation of nanotubes on the two substrates that account for the
 303 difference in the photocatalytic performance. The microreactor was applied to
 304 the inactivation of *E. coli* O157:H7. The the TNA_{mesh} microreactor was able
 305 to achieve >99% inactivation of *E. coli* at a flow rate of 50 $\mu\text{L}/\text{min}$ (≈ 100
 306 mW/cm^2 AM 1.5 light). The device can be used as an integrated platform
 307 for degradation of an array of organic and biological contaminants. The device
 308 can also be integrated with a biological or organic pollutant quantification unit
 309 which can enable real-time optimization of the flow rate/throughput based on
 310 amount of pollutant present.

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