Supporting Information

Inactivation of *E. coli*, Bacteriophage MS2 and *Bacillus* Spores under UV/H_2O_2 and UV/Peroxydisulfate Advanced Disinfection Conditions

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Text S1. Chemicals and reagents

H_2O_2 (wt. 30%) was purchased from Fisher Scientific Co. (Pittsburgh, PA). PDS (98%) was purchased from Alfa Aesar (Ward Hill, MA). TBA (99.5%) was purchased from Sigma Aldrich Inc. (St. Louis, MO). $NaHCO_3$, K_2HPO_4, KH_2PO_4 and $MgSO_4$ were obtained from Fisher Scientific Co. Nutrient broth, agar, tryptone, yeast extract, and glucose were obtained from VWR International Inc. (West Chester, PA).

Text S2. Preparation of the culture stock of microbial surrogates and experimental setup

E. coli (ATCC 15597) was inoculated in nutrient broth (VWR BD 234000) and grown for 18 h at 37°C. The culture was then transferred into a 50-mL tube, which was centrifuged at 1,000 g for 10 min. The supernatant was discarded. The bacteria palette was washed two more times with 50 mL of phosphate-buffered solution (PBS) (3 mM phosphate at pH 7). Stock suspension of *E. coli* was prepared by resuspending the final pellet in 2 mL PBS and stored at 4 ^{o}C prior to use. To achieve an initial density of *E. coli* around 4×10^6 CFU/mL for each disinfection experiment, the stock suspension of *E. coli* was spiked in reaction solution by a dilution factor of 1,000–10,000. Disinfection experiments were initiated by placing the petri dish (containing 3.0 mM PBS (pH 7), 0.3 mM oxidant and microbial surrogates, with or without scavengers) under UV exposure. Preliminary test showed that the pH was stable during the disinfection experiments. For each condition, at least triplicate experiments were conducted. For each sample, a ten-fold serial dilution was performed up to 1/10,000 dilution ratio using 30 mM PBS at pH 7.1. 0.1-mL aliquot of each diluted solution was inoculated onto each of three replicates of 47-mm sterile Petri dishes containing nutrient agar (8 g/L nutrient broth + 15 g/L agar,). Colony forming units (CFU) were counted after incubation at 37 ^{o}C for 24 h.

The stocks of bacteriophage MS2 (ATCC 15597-B1) were prepared using *E. coli* (ATCC 15597) as the host. *E. coli* host was grown and assayed in a medium containing 1% tryptone, 0.05% glucose, 0.8% NaCl, 0.03% $CaCl_2 \cdot 2H_2O$ and 0.1% yeast extract. Quantification of MS2 employed double-agar layer method of plaque assay. The incubation temperature was 37°C. MS2 stocks were prepared from the top agar layer, which was transferred into a 50-mL centrifuge tube and vigorously mixed with 10 mL of phosphate-buffered saline (PBS) (150 mM sodium phosphate plus 150 mM sodium chloride). After centrifugation at 3,000 g for 15 min, the supernatant containing MS2 was saved. To achieve an initial density of bacteriophage MS2 around 3×10^6 PFU/mL for each disinfection experiment, the stock suspension of MS2 was spiked in reaction solution by a dilution factor of 1,000–10,000. Preliminary tests showed that the carryover of growth media posed negligible influence on the UV-based ADP performance. For each sample, a ten-fold serial dilution was performed up to 1/10,000 dilution ratio using 30 mM PBS at pH 7.1. Three replicates of 0.3-mL aliquot of each diluted solution was mixed with 0.1 mL host *E. coli* suspension and 4.5 mL soft agar liquid (at 50^{o}C). The mixture was then transferred onto a 47-mm sterile Petri dish containing bottom agar. Plague forming units (PFU) were counted after incubation at 37 ^{o}C for 12 h.

Stocks of *Bacillus subtilis* spores were prepared from a freeze-dried pellet of *B. subtilis* (ATCC

6633), which was rehydrated aseptically using a nutrient broth and incubated at 37 ^{o}C for 18 h. Bacterial cells were then harvested in similar fashion as *E. coli*. Several 47-mm sterile Petri dishes containing 1/10 diluted nutrient agar (0.8 g/L nutrient broth + 15 g/L agar,) were subsequently inoculated and incubated at 37 ^{o}C for 5-6 days to induce sporulation. After incubation, *B. subtilis* spores were collected into 50-mL conical tubes by rinsing the agar with PBS. The spores were cleaned by repeated centrifugation at 3,500 g for 10 min and resuspended in PBS three times. In order to inactivate any remaining vegetative cells, the stock solution was heat treated at 80 ^{o}C for over 20 min before each experiment. To achieve an initial density of *B. subtilis* spores around 4 × 10^6 CFU/mL for each disinfection experiment, the stock suspension of *B. subtilis* spores was spiked in reaction solution by a dilution factor of 1,000–10,000. For each sample, a ten-fold serial dilution was performed up to 1/10,000 dilution ratio using 30 mM PBS at pH 7.1. Three replicates of 0.1-mL aliquot of each diluted solution was inoculated onto three replicate 47-mm sterile Petri dishes containing nutrient agar (8 g/L nutrient broth + 15 g/L agar,). Colony forming units (CFU) were counted after incubation at 37 ^{o}C for 24 h.

Text S3. Conversion between UV fluence and area-metric light intensity

UV fluence (I_λ, in Einstein·L^{-1}) and area-metric light intensity (I_λ', in J·cm^{-2}) can be converted using the equation below:

$$I_\lambda = \frac{I_\lambda' \cdot 0.25\pi D^2}{V} \cdot \frac{1}{N_A \cdot \frac{h \cdot c}{\lambda}} \qquad \text{(Einstein} \cdot \text{L}^{-1}\text{)} \qquad \text{(S1)}$$

I_λ' = area-metric light intensity, J·cm^{-2};

D = reactor diameter, cm;

V = the volume of reaction solution, L;

N_A = Avogadro's number, 6.022×10^{23};

h = Planck's constant, 6.626×10^{-34} $m^2 \cdot kg \cdot s^{-1}$;

c = the speed of light, 3×10^8 $m \cdot s^{-1}$;

λ = wavelength, m.

Text S4. Model validation

The concentrations of hydroxyl radical, sulfate radical and carbonate radical were measured in systems with UV/H_2O_2, UV/PDS and UV/H_2O_2/$NaHCO_3$, respectively. The degradation of nitrobenzene, anisole and *para*-nitroaniline, respectively, was monitored to calculate radical concentrations. The calculation method was detailed in Zhang et al. (2015).[1] The results (Table S3) showed that the model used in this study could successfully predict radical concentrations.

Text S5. Estimation of diffusion-controlled limits

The commonly referred "diffusion-controlled limits", which is around 10^9–10^{10} $M^{-1}s^{-1}$ is derived based on the assumption that the reactants are approximately equal in size in the bimolecular association reaction. For a reaction A + B → product, the reaction rate, k, can be expressed as:[2]

$$k = (2k_BT)/(3\eta)*((r_A/r_B) + (r_B/r_A) + 2)$$

where k_BT is the product of the Boltzmann constant and the absolute temperature; η is the solvent viscosity; r_A and r_B are the radii of molecules A and B, respectively. Therefore, when A and B are approximately equal in size, one finds $k = 8k_BT/3\eta$, which corresponds to $k = 6.6\times10^9$ $M^{-1}s^{-1}$ at

20°C. However, in the case of radicals (R) inactivating microbial surrogates (MS), r_{MS}/r_R is higher than 100 (e.g., the size of MS2 is about 27 nm,[3] and the bond length of hydroxyl radical is around 0.1 nm.[4]). Therefore, it is possible that $k > 6.6\times10^{11}$ $M^{-1}s^{-1}$ (i.e., ~4×10^{13} $M^{-1}min^{-1}$). Considering the values in Table 2 are all based on $\log_{10}$ of inactivation (instead of natural log), the upper limit of slope values should be 1.74×10^{13} $M^{-1}min^{-1}$, which is higher than all the slope values obtained in this study.

Text S6. Unit conversion of H_2O_2 and PDS

The price of H_2O_2 (50% by weight) on Alibaba.com was $400 per ton (April, 2015). Considering the average electricity cost is around 12 cent/kWh in the U.S., one milligram of H_2O_2 can be converted to 6.67×10^{-6} kWh. As for PDS, the price of sodium persulfate on Alibaba.com was $1130 per ton (April, 2015). Therefore, with the same electricity cost, one milligram of PDS can be converted to 9.42×10^{-6} kWh.

Text S7. Demonstration of EE/O calculation

Example conditions: surface water matrix, H_2O_2 is at 0.19 mM, photo fluence is at 1.0×10^{-7} Einstein·L^{-1}·s^{-1}, reaction time (t) is 4 min.

Calculation of -log $(N/N_0)_t$: Applying 0.19 mM of H_2O_2 and 1.0×10^{-7} Einstein·L^{-1}·s^{-1} into the Matlab Simbiology program, the hydroxyl radical concentration ([·OH]), sulfate radical concentration ($[SO_4^{\cdot-}]$) and carbonate radical concentration ($[CO_3^{\cdot-}]$) were calculated to be

5.35×10^{-14} M, 4.54×10^{-22} M and 2.07×10^{-12} M, respectively. The photo fluence, [$\cdot$OH], [$SO_4^{\cdot-}$] and [$CO_3^{\cdot-}$] were then used in Eqn. 10 in the main text with the reaction time of 4 min to calculate the overall reduction of bacteriophage MS2 (-log $(N/N_0)_t = 2.42$).

Calculation of energy input over volume P/V: The photo fluence rate is at 1.0×10^{-7} Einstein$\cdot$L$^{-1}\cdot$s^{-1}. Since one mole of photons (1 Einstein) at 254 nm is equivalent to 0.1308 kWh of energy,[5] the energy received by the system was 1.31×10^{-8} kWh$\cdot$L$^{-1}\cdot$s^{-1}. It is also assumed that energy efficiency of UV lamps was about 25%,[5] and energy input was 5.23×10^{-8} kWh$\cdot$L$^{-1}\cdot$s^{-1}. With the exposure time of 4 min, the energy input P/V is equal to 1.26×10^{-5} kWh$\cdot$L^{-1}.

Substituting -log $(N/N_0)_t = 2.42$, P/V = 1.26×10^{-5} kWh$\cdot$L^{-1} and [H_2O_2] = 0.19 mM in Eqn. 11 in the main text, EE/O was calculated to be 2.29×10^{-5} kWh$\cdot$L^{-1}.

Table S1. **Characteristics of the Water Samples.**

Water	pH	A_{254} (cm^{-1})	DOC ($mg\ C{\cdot}L^{-1}$)	TIC ($mg\ C{\cdot}L^{-1}$)	Nitrate (mM)	Sulfate (mM)	Chloride (mM)
Surface water	7.4	0.069	3.07	5.63	0.017	0.022	0.092
Wastewater	7.6	0.085	7.33	11.76	1.07	0.46	1.64

DOC= dissolved organic carbon; TIC = total inorganic carbon.

Table S2. Elementary reactions

No.	Reaction	Rate Constant	Reference
1	$H_2O_2/HO_2^- \xrightarrow{h\upsilon} 2\cdot {}^{\bullet}OH$ $S_2O_8^{2-} \xrightarrow{h\upsilon} 2\cdot SO_4^{\bullet-}$ $NO_3^- \xrightarrow{h\upsilon} NO_2^{\bullet} + {}^{\bullet}OH$	$r_{UV,oxidant}$ = $\Phi I_0 f_{oxidant} F_s$/[oxidant] Φ = quantum yield of H_2O_2/PDS/nitrate; I_0 = light intensity; $f_{oxidant}$ = fraction of light absorbed by oxidant = $\frac{\varepsilon_{oxidant}[oxidant]l}{A_{solution}}$; F_s = fraction of light absorbed by the system = $1-e^{-A_{solution}}$; [oxidant] = concentration of H_2O_2, PDS or nitrate	a
2	$H^+ + OH^- \rightarrow H_2O$	1.0×10^{11} $M^{-1}\cdot s^{-1}$	a
3	$H_2O \rightarrow H^+ + OH^-$	1.0×10^{-3} s^{-1}	a
4	$H^+ + HO_2^- \rightarrow H_2O_2$	5.0×10^{10} $M^{-1}\cdot s^{-1}$	a
5	$H_2O_2 \rightarrow H^+ + HO_2^-$	1.3×10^{-1} s^{-1}	a
6	$H^+ + SO_5^{2-} \rightarrow HSO_5^-$	5.0×10^{10} $M^{-1}\cdot s^{-1}$	a
7	$HSO_5^- \rightarrow H^+ + SO_5^{2-}$	19.9 s^{-1}	a
8	$H^+ + O_2\cdot^- \rightarrow HO_2\cdot$	5×10^{10} $M^{-1}\cdot s^{-1}$	a
9	$HO_2^{\cdot} \rightarrow H^+ + O_2^{\cdot-}$	7.9×10^{5} s^{-1}	a
10	$HCO_3^- + H^+ \rightarrow H_2CO_3$	5.0×10^{10} $M^{-1}\cdot s^{-1}$	a
11	$H_2CO_3 \rightarrow HCO_3^- + H^+$	2.5×10^{4} s^{-1}	a
12	$CO_3^{2-} + H^+ \rightarrow HCO_3^-$	5×10^{10} $M^{-1}\cdot s^{-1}$	a
13	$HCO_3^- \rightarrow CO_3^{2-} + H^+$	2.5 s^{-1}	a
14	$H_2PO_4^- + H^+ \rightarrow H_3PO_4$	5×10^{10} $M^{-1}\cdot s^{-1}$	a

15	$H_3PO_4 \rightarrow H_2PO_4^- + H^+$	$3.97\times10^8\ s^{-1}$	a
16	$HPO_4^{2-} + H^+ \rightarrow H_2PO_4^-$	$5\times10^{10}\ M^{-1}\cdot s^{-1}$	a
17	$H_2PO_4^- \rightarrow HPO_4^{2-} + H^+$	$3.2\times10^3\ s^{-1}$	a
18	$PO_4^{3-} + H^+ \rightarrow HPO_4^{2-}$	$5\times10^{10}\ M^{-1}\cdot s^{-1}$	a
19	$HPO_4^{2-} \rightarrow PO_4^{3-} + H^+$	$2.5\times10^{-2}\ s^{-1}$	a
20	$^{\cdot}OH + {^{\cdot}OH} \rightarrow H_2O_2$	$5.5\times10^9\ M^{-1}\cdot s^{-1}$	a
21	$^{\cdot}OH + H_2O_2 \rightarrow HO_2^{\cdot} + H_2O$	$2.7\times10^7\ M^{-1}\cdot s^{-1}$	a
22	$^{\cdot}OH + HO_2^- \rightarrow HO_2^{\cdot} + OH^-$	$7.5\times10^9\ M^{-1}\cdot s^{-1}$	a
23	$^{\cdot}OH + S_2O_8^{2-} \rightarrow S_2O_8^{\cdot -} + OH^-$	$1.4\times10^7\ M^{-1}\cdot s^{-1}$	a
24	$^{\cdot}OH + HO_2^{\cdot} \rightarrow O_2 + H_2O$	$6.6\times10^9\ M^{-1}\cdot s^{-1}$	a
25	$^{\cdot}OH + O_2^{\cdot -} \rightarrow O_2 + OH^-$	$7.0\times10^9\ M^{-1}\cdot s^{-1}$	a
26	$HO_2^{\cdot} + HO_2^{\cdot} \rightarrow H_2O_2 + O_2$	$8.3\times10^9\ M^{-1}\cdot s^{-1}$	a
27	$HO_2^{\cdot} + O_2^{\cdot -} \rightarrow HO_2^- + O_2$	$9.7\times10^7\ M^{-1}\cdot s^{-1}$	a
28	$HO_2^{\cdot} + H_2O_2 \rightarrow O_2 + {^{\cdot}OH} + H_2O$	$3.0\ M^{-1}\cdot s^{-1}$	a
29	$O_2^{\cdot -} + H_2O_2 \rightarrow O_2 + {^{\cdot}OH} + OH^-$	$0.13\ M^{-1}\cdot s^{-1}$	a
30	$^{\cdot}OH + CO_3^{2-} \rightarrow CO3^- + OH^-$	$3.9\times10^8\ M^{-1}\cdot s^{-1}$	a
31	$^{\cdot}OH + HCO_3^- \rightarrow CO_3^{\cdot -} + H_2O$	$8.6\times10^6\ M^{-1}\cdot s^{-1}$	a
32	$H_2O_2 + CO_3^{\cdot -} \rightarrow HCO_3^- + HO_2\cdot$	$4.3\times10^5\ M^{-1}\cdot s^{-1}$	a
33	$HO_2^- + CO_3^{\cdot -} \rightarrow CO_3^{2-} + HO_2\cdot$	$3.0\times10^7\ M^{-1}\cdot s^{-1}$	a
34	$^{\cdot}OH + CO_3^{\cdot -} \rightarrow$ product	$3.0\times10^9\ M^{-1}\cdot s^{-1}$	a
35	$O_2^{\cdot -} + CO_3^{\cdot -} \rightarrow CO_3^{2-} + O_2$	$6.0\times10^8\ M^{-1}\cdot s^{-1}$	a
36	$CO_3^{\cdot -} + CO_3^{\cdot -} \rightarrow$ product	$3.0\times10^7\ M^{-1}\cdot s^{-1}$	a
37	$^{\cdot}OH + HPO_4^{2-} \rightarrow HPO_4^{\cdot} + OH^-$	$1.5\times10^5\ M^{-1}\cdot s^{-1}$	a
38	$\cdot OH + H_2PO_4^- \rightarrow HPO_4^{\cdot -} + H_2O$	$2.0\times10^4\ M^{-1}\cdot s^{-1}$	a

39	$H_2O_2 + HPO_4^{\cdot -} \rightarrow H_2PO_4^- + HO_2^\cdot$	2.7×10^7 $M^{-1}\cdot s^{-1}$	a
40	$SO_4^{\cdot -} + OH^- \rightarrow SO_4^{2-} + {}^\cdot OH$	7×10^7 $M^{-1}\cdot s^{-1}$	a
41	$SO_4^{\cdot -} + H_2O \rightarrow HSO_4^- + {}^\cdot OH$	660 s^{-1}	a
42	$SO_4^{\cdot -} + {}^\cdot OH \rightarrow HSO_5^-$	1.0×10^{10} $M^{-1}\cdot s^{-1}$	a
43	$SO_4^{\cdot -} + HSO_5^- \rightarrow SO_5^{\cdot -} + HSO_4^-$	1.0×10^6 $M^{-1}\cdot s^{-1}$	a
44	$SO_4^{\cdot -} + SO_5^{2-} \rightarrow SO_5^{\cdot -} + SO_4^{2-}$	1.0×10^8 $M^{-1}\cdot s^{-1}$	a
45	$SO_5^{\cdot -} + SO_5^{\cdot -} \rightarrow SO_4^{\cdot -} + SO_4^{\cdot -} + O_2$	2.1×10^8 $M^{-1}\cdot s^{-1}$	a
46	$SO_5^{\cdot -} + SO_5^{\cdot -} \rightarrow S_2O_8^{2-} + O_2$	2.2×10^8 $M^{-1}\cdot s^{-1}$	a
47	$SO_4^{\cdot -} + SO_4^{\cdot -} \rightarrow S_2O_8^{2-}$	7.0×10^8 $M^{-1}\cdot s^{-1}$	a
48	$SO_4^{\cdot -} + S_2O_8^{2-} \rightarrow S_2O_8^{\cdot -} + SO_4^{2-}$	6.5×10^5 $M^{-1}\cdot s^{-1}$	a
49	$S_2O_8^{2-} + CO_3^{\cdot -} \rightarrow CO_3^{2-} + S_2O_8^{\cdot -}$	3.0×10^7 $M^{-1}\cdot s^{-1}$	a
50	$SO_4^{\cdot -} + HPO_4^{2-} \rightarrow HPO_4^{\cdot -} + SO_4^{2-}$	1.2×10^6 $M^{-1}\cdot s^{-1}$	a
51	$SO_4^{\cdot -} + H_2PO_4^- \rightarrow HPO_4^{\cdot -} + HSO_4^-$	5.0×10^4 $M^{-1}\cdot s^{-1}$	a
52	$SO_4^{\cdot -} + HCO_3^- \rightarrow CO_3^{\cdot -} + HSO_4^-$	2.8×10^6 $M^{-1}\cdot s^{-1}$	a
53	$SO_4^{\cdot -} + CO_3^{2-} \rightarrow CO_3^{\cdot -} + SO_4^{2-}$	6.1×10^6 $M^{-1}\cdot s^{-1}$	a
54	${}^\cdot OH + Cl^- \rightarrow ClOH^{\cdot -}$	4.3×10^9 $M^{-1}\cdot s^{-1}$	a
55	$ClOH^{\cdot -} \rightarrow {}^\cdot OH + Cl^-$	6.1×10^9 $M^{-1}\cdot s^{-1}$	a
56	$SO_4^{\cdot -} + Cl^- \rightarrow SO_4^{2-} + Cl^\cdot$	3.0×10^8 $M^{-1}\cdot s^{-1}$	a
57	$SO_4^{2-} + Cl^\cdot \rightarrow SO_4^{\cdot -} + Cl^-$	2.5×10^8 $M^{-1}\cdot s^{-1}$	a
58	$ClOH^{\cdot -} + H^+ \rightarrow Cl^\cdot + H_2O$	2.1×10^{10} $M^{-1}\cdot s^{-1}$	a
59	$ClOH^{\cdot -} + Cl^- \rightarrow Cl_2^{\cdot -} + OH^-$	1.0×10^4 $M^{-1}\cdot s^{-1}$	a
60	$Cl^\cdot + H_2O \rightarrow ClOH^{\cdot -} + H^+$	4.5×10^3 $M^{-1}\cdot s^{-1}$	a
61	$Cl^\cdot + OH^- \rightarrow ClOH^{\cdot -}$	1.8×10^{10} $M^{-1}\cdot s^{-1}$	a
62	$Cl^\cdot + H_2O_2 \rightarrow HO_2^\cdot + Cl^- + H^+$	2.0×10^9 $M^{-1}\cdot s^{-1}$	a

63	$Cl^{\cdot} + Cl^{-} \rightarrow Cl_2^{\cdot-}$	8.5×10^{9} $M^{-1}\cdot s^{-1}$	a
64	$Cl^{\cdot} + Cl^{\cdot} \rightarrow Cl_2$	8.8×10^{7} $M^{-1}\cdot s^{-1}$	a
65	$Cl^{\cdot} + HOCl \rightarrow ClO^{\cdot} + H^{+} + Cl^{-}$	3.0×10^{9} $M^{-1}\cdot s^{-1}$	a
66	$Cl^{\cdot} + OCl^{-} \rightarrow ClO^{\cdot} + Cl^{-}$	8.3×10^{9} $M^{-1}\cdot s^{-1}$	a
67	$Cl_2^{\cdot-} \rightarrow Cl^{\cdot} + Cl^{-}$	6.0×10^{4} $M^{-1}\cdot s^{-1}$	a
68	$Cl_2 + OH \rightarrow HOCl + Cl^{-}$	1.0×10^{9} $M^{-1}\cdot s^{-1}$	a
69	$Cl_2^{\cdot-} + Cl_2^{\cdot-} \rightarrow Cl_2 + 2Cl^{-}$	9.0×10^{8} $M^{-1}\cdot s^{-1}$	a
70	$Cl_2^{\cdot-} + Cl^{\cdot} \rightarrow Cl_2 + Cl^{-}$	2.1×10^{9} $M^{-1}\cdot s^{-1}$	a
71	$Cl_2\cdot^{-} + H_2O_2 \rightarrow HO_2\cdot + 2Cl^{-} + H^{+}$	1.4×10^{5} $M^{-1}\cdot s^{-1}$	a
72	$Cl_2^{\cdot-} + HO_2^{\cdot} \rightarrow O_2 + 2Cl^{-} + H^{+}$	3.0×10^{9} $M^{-1}\cdot s^{-1}$	a
73	$Cl_2^{\cdot-} + O_2^{\cdot-} \rightarrow O_2 + 2Cl^{-}$	2.0×10^{9} $M^{-1}\cdot s^{-1}$	a
74	$Cl_2^{\cdot-} + H_2O \rightarrow Cl^{-} + HClOH$	23.38 $M^{-1}\cdot s^{-1}$	a
75	$Cl_2^{\cdot-} + OH^{-} \rightarrow Cl^{-} + ClOH^{\cdot-}$	4.5×10^{7} $M^{-1}\cdot s^{-1}$	a
76	$HClOH \rightarrow ClOH^{\cdot-} + H^{+}$	1.0×10^{8} $M^{-1}\cdot s^{-1}$	a
77	$HClOH \rightarrow Cl^{\cdot} + H_2O$	1.0×10^{2} $M^{-1}\cdot s^{-1}$	a
78	$HClOH + Cl^{-} \rightarrow Cl_2\cdot^{-} + H_2O$	5.0×10^{9} $M^{-1}\cdot s^{-1}$	a
79	$Cl_2 + Cl^{-} \rightarrow Cl_3^{-}$	2.0×10^{4} $M^{-1}\cdot s^{-1}$	a
80	$Cl_3^{-} \rightarrow Cl_2 + Cl^{-}$	1.1×10^{5} $M^{-1}\cdot s^{-1}$	a
81	$Cl_3^{-} + HO_2^{\cdot} \rightarrow Cl_2^{\cdot-} + HCl + O_2$	1.0×10^{9} $M^{-1}\cdot s^{-1}$	a
82	$Cl_3^{-} + O_2^{\cdot-} \rightarrow Cl_2^{\cdot-} + Cl^{-} + O_2$	3.8×10^{9} $M^{-1}\cdot s^{-1}$	a
83	$Cl_2 + H_2O \rightarrow Cl^{-} + HOCl + H^{+}$	0.27 $M^{-1}\cdot s^{-1}$	a
84	$Cl^{-} + HOCl + H^{+} \rightarrow Cl_2 + H_2O$	18.2 $M^{-2}\cdot s^{-1}$	a
85	$Cl_2 + H_2O_2 \rightarrow O_2 + 2HCl$	1.3×10^{4} $M^{-1}\cdot s^{-1}$	a
86	$Cl_2 + O_2\cdot^{-} \rightarrow O_2 + Cl_2\cdot^{-}$	1.0×10^{9} $M^{-1}\cdot s^{-1}$	a

87	$Cl_2 + HO_2^{\cdot} \rightarrow H^+ + O_2 + Cl_2^{\cdot -}$	1.0×10^9 $M^{-1}\cdot s^{-1}$	a
88	$H^+ + OCl^- \rightarrow HOCl$	5.0×10^{10} $M^{-1}\cdot s^{-1}$	a
89	$HOCl \rightarrow H^+ + OCl^-$	1.4×10^3 s^{-1}	a
90	$HOCl + H_2O_2 \rightarrow HCl + H_2O + O_2$	1.1×10^4 $M^{-1}\cdot s^{-1}$	a
91	$OCl^- + H_2O_2 \rightarrow Cl^- + H_2O + O_2$	1.7×10^5 $M^{-1}\cdot s^{-1}$	a
92	$HOCl + {}^{\cdot}OH \rightarrow ClO^{\cdot} + H_2O$	2.0×10^9 $M^{-1}\cdot s^{-1}$	a
93	$HOCl + O_2^{\cdot -} \rightarrow Cl^{\cdot} + OH^- + O_2$	7.5×10^6 $M^{-1}\cdot s^{-1}$	a
94	$HOCl + HO_2^{\cdot} \rightarrow Cl^{\cdot} + OH^- + O_2$	7.5×10^6 $M^{-1}\cdot s^{-1}$	a
95	$OCl^- + {}^{\cdot}OH \rightarrow ClO^{\cdot} + OH^-$	8.8×10^9 $M^{-1}\cdot s^{-1}$	a
96	$OCl^- + O_2\cdot^- + H_2O \rightarrow Cl\cdot + 2OH^- + O_2$	2×10^8 $M^{-1}\cdot s^{-1}$	a
97	$OCl^- + CO_3\cdot^- \rightarrow OCl\cdot + CO_3^{2-}$	5.7×10^5 $M^{-1}\cdot s^{-1}$	a
98	$Cl\cdot + CO_3^{2-} \rightarrow Cl^- + CO_3\cdot^-$	5.0×10^8 $M^{-1}\cdot s^{-1}$	a
99	$Cl^{\cdot} + HCO_3^- \rightarrow Cl^- + CO_3^{\cdot -} + H^+$	2.2×10^8 $M^{-1}\cdot s^{-1}$	a
100	$Cl_2\cdot^- + CO_3^{2-} \rightarrow 2Cl^- + CO_3\cdot^-$	1.6×10^8 $M^{-1}\cdot s^{-1}$	a
101	$Cl_2^{\cdot -} + HCO_3^- \rightarrow 2Cl^- + CO_3^{\cdot -} + H^+$	8.0×10^7 $M^{-1}\cdot s^{-1}$	a
102	$H^+ + Cl^- \rightarrow HCl$	5.0×10^{10} $M^{-1}\cdot s^{-1}$	a
103	$HCl \rightarrow H^+ + Cl^-$	8.6×10^{16} s^{-1}	a
104	${}^{\cdot}OH + NH_3 \rightarrow {}^{\cdot}NH_2 + H_2O$	9.0×10^7 $M^{-1}\cdot s^{-1}$	a
105	$SO_4^{\cdot -} + NH_3 \rightarrow {}^{\cdot}NH_2 + SO_4^{2-} + H^+$	1.4×10^7 $M^{-1}\cdot s^{-1}$	a
106	$\cdot NH_2 + O_2 \rightarrow NH_2O_2^{\cdot}$	10^9 $M^{-1}\cdot s^{-1}$	a
107	$NH_2O_2^{\cdot} \rightarrow \cdot NO + H_2O$	$\sim7\times10^5$ $M^{-1}\cdot s^{-1}$	a
108	$\cdot NO + O_2\cdot^- \rightarrow ONOO^-$	6.7×10^9 $M^{-1}\cdot s^{-1}$	a
109	$ONOO^- \rightarrow \cdot NO + O_2\cdot^-$	2.0×10^{-2} s^{-1}	a
110	$ONOO^- + CO_2 \rightarrow \cdot NO_2 + CO_3\cdot^-$	2.9×10^4 $M^{-1}\cdot s^{-1}$	a
111	$ONOO^- \rightarrow NO_3^-$	$\sim8\times10^{-6}$ s^{-1}	a

112	$ONOO^- \rightarrow \cdot NO_2 + O\cdot^-$	$\sim 10^{-6}\ s^{-1}$	a
113	$\cdot NO_2 + O\cdot^- \rightarrow ONOO^-$	$3.5\times10^{9}\ M^{-1}\cdot s^{-1}$	a
114	$ONOO^- + {}^{\cdot}OH \rightarrow \cdot NO + O_2 + OH^-$	$4.8\times10^{9}\ M^{-1}\cdot s^{-1}$	a
115	$ONOO^- + CO_3\cdot^- \rightarrow \cdot NO + O_2 + CO_3^{2-}$	$3.7\times10^{6}\ M^{-1}\cdot s^{-1}$	a
116	$\cdot NO_2 + {}^{\cdot}OH \rightarrow ONOOH$	$4.5\times10^{9}\ M^{-1}\cdot s^{-1}$	a
117	$ONOOH \rightarrow \cdot NO_2 + {}^{\cdot}OH$	$3.5\times10^{-1}\ s^{-1}$	a
118	$\cdot NO + HO_2^{\cdot} \rightarrow ONOOH$	$3.2\times10^{9}\ M^{-1}\cdot s^{-1}$	a
119	$ONOOH \rightarrow NO_3^- + H^+$	$9.0\times10^{-1}\ s^{-1}$	a
120	$ONOOH + H^+ \rightarrow NO_3^- + 2H^+$	$4.3\ M^{-1}\ s^{-1}$	a
121	$ONOOH + H_2O + H^+ \rightarrow HNO_2 + H_2O_2 + H^+$	$1.1\times10^{-1}\ M^{-2}\cdot s^{-1}$	a
122	$HNO_2 + H_2O_2 + H^+ \rightarrow ONOOH + H_2O + H^+$	$9.6\times10^{3}\ M^{-2}\cdot s^{-1}$	a
123	$\cdot NO_2 + O_2\cdot^- \rightarrow O_2NOO^-$	$4.5\times10^{9}\ M^{-1}\cdot s^{-1}$	a
124	$O_2NOO^- \rightarrow \cdot NO_2 + O_2\cdot^-$	1.0	a
125	$O_2NOO^- \rightarrow NO_2^- + O_2$	1.4	a
126	$\cdot NO_2 + HO_2^{\cdot} \rightarrow O_2NOOH$	$1.8\times10^{9}\ M^{-1}\cdot s^{-1}$	a
127	$O_2NOOH \rightarrow \cdot NO_2 + HO_2$	$2.6\times10^{-2}\ s^{-1}$	a
128	$H^+ + ONOO^- \rightarrow ONOOH$	$5\times10^{10}\ M^{-1}\cdot s^{-1}$	assumed
129	$ONOOH \rightarrow H^+ + ONOO^-$	$1.25\times10^{4}\ s^{-1}$	calculated
130	$H^+ + O_2NOO^- \rightarrow O_2NOOH$	$5\times10^{10}\ M^{-1}\cdot s^{-1}$	assumed
131	$O_2NOOH \rightarrow H^+ + O_2NOO^-$	$6.9\times10^{4}\ s^{-1}$	calculated
132	$H^+ + NO_2^- \rightarrow HNO_2$	$5\times10^{10}\ M^{-1}\cdot s^{-1}$	assumed
133	$HNO_2 \rightarrow H^+ + NO_2^-$	$2.51\times10^{7}\ M^{-1}\cdot s^{-1}$	calculated
134	$CO_3\cdot^- + NH_3 \rightarrow {}^{\cdot}NH_2 + HCO_3^-$	$\sim 3\times10^{4}\ M^{-1}\cdot s^{-1}$	a
135	$CO_3\cdot^- + {}^{\cdot}NH_2 \rightarrow NH_2O^- + CO_2$	$7.5\times10^{9}\ M^{-1}\cdot s^{-1}$	a
136	$\cdot NO_2 + \cdot NO_2 \rightarrow N_2O_4$	$4.5\times10^{8}\ M^{-1}\cdot s^{-1}$	a

137	$N_2O_4 \rightarrow \cdot NO_2 + \cdot NO_2$	6.9×10^3 s^{-1}	a
138	$N_2O_4 \rightarrow NO_2^- + NO_3^- + 2H^+$	1×10^3 s^{-1}	a
139	$\cdot NO_2 + \cdot NO \rightarrow N_2O_3$	1.1×10^9 $M^{-1}\cdot s^{-1}$	a
140	$N_2O_3 \rightarrow NO_2^- + NO_2^- + 2H^+$	530 s^{-1}	a
141	$O^{\cdot-} + H_2O \rightarrow {}^{\cdot}OH + OH^-$	9.4×10^7 $M^{-1}\cdot s^{-1}$	b
142	${}^{\cdot}OH + OH^- \rightarrow O^{\cdot-} + H_2O \rightarrow$	1.3×10^{10} $M^{-1}\cdot s^{-1}$	b
143	DOM + ${}^{\cdot}OH \rightarrow$ product	3.9×10^8 $M^{-1}\cdot s^{-1}$	c
144	DOM + $CO_3\cdot^- \rightarrow$ product	2.3×10^4 $M^{-1}\cdot s^{-1}$	d
145	DOM + $SO_4\cdot^- \rightarrow$ product	1.0×10^7 $M^{-1}\cdot s^{-1}$	estimated
146	TBA + ${}^{\cdot}OH \rightarrow$ product	7.6×10^8 $M^{-1}\cdot s^{-1}$	b
147	TBA + $SO_4\cdot^- \rightarrow$ product	9.1×10^5 $M^{-1}\cdot s^{-1}$	b
148	$H_2O_2 + SO_4\cdot^- \rightarrow HO_2^{\cdot-} + SO_4^{2-} + H^+$	1.2×10^7 $M^{-1}\cdot s^{-1}$	b

a Zhang et al. (2015)[1]
b NIST[6]
c Brezonik et al. (1998)[7]
d Canonica et al. (2005)[8]

Table S3. Radical concentrations determined by experiments and by kinetic modeling.

System	Radical probe	Radical species	Measured by exp. (M)	Predicted by model (M)
UV/H_2O_2	Nitrobenzene	Hydroxyl radical	4.2×10^{-15}	4.4×10^{-15}
UV/PDS	Nitrobenzene, Anisole	Sulfate radical	1.7×10^{-15}	1.4×10^{-15}
UV/H_2O_2/$NaHCO_3$	Nitrobenzene, *para*-nitroaniline	Carbonate radical	1.1×10^{-12}	9.8×10^{-13}

Table S4. UV fluence (Einstein·L^{-1}) for experiments in Figure 2.

System	*E. coli*	MS2	*Bacillus* spores
7*/7	8.9×10^{-7}	2.2×10^{-6}	1.6×10^{-6}
6*/6	8.9×10^{-7}	4.4×10^{-6}	1.6×10^{-6}
5*/5	1.1×10^{-6}	4.4×10^{-6}	1.6×10^{-6}

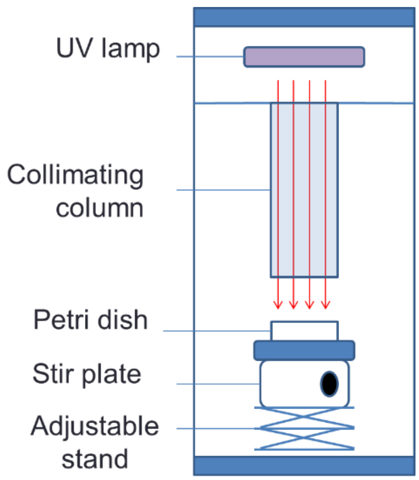

Figure S1. Illustration of collimated beam photoreactor.

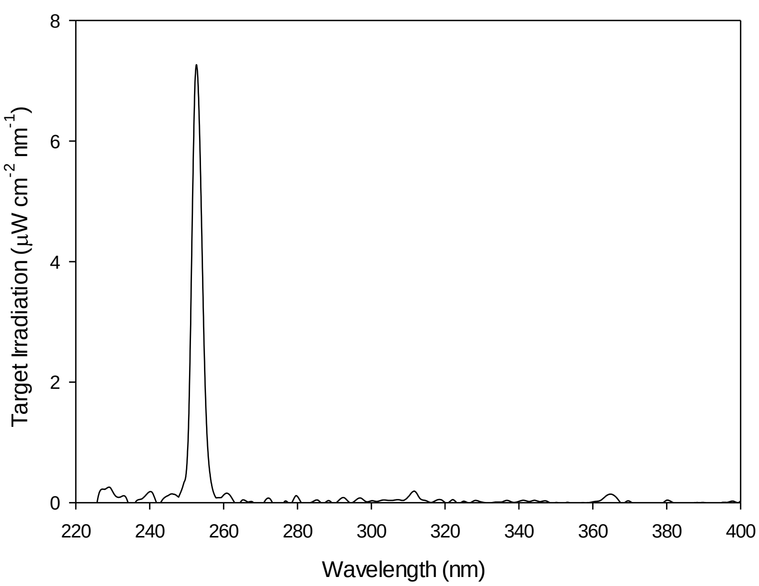

Figure S2. Light spectra of low pressure UV lamp.

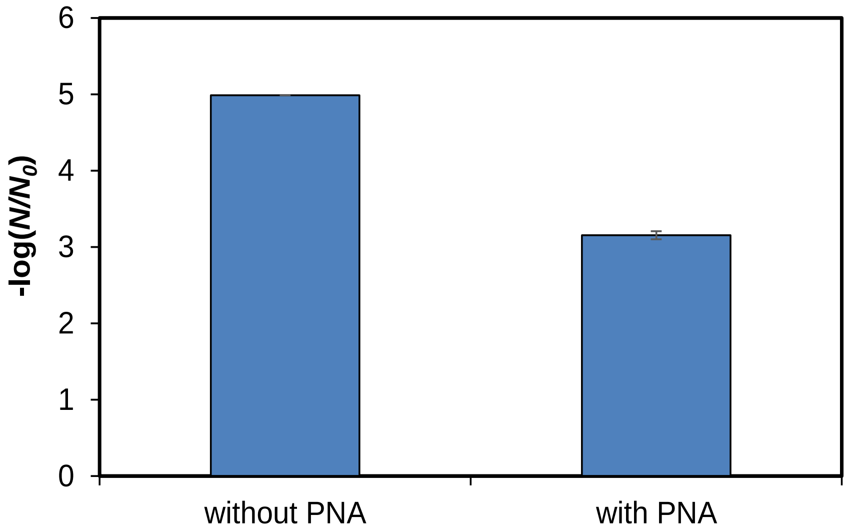

Figure S3. Inactivation of MS2 in the UV/H_2O_2/$NaHCO_3$ system with or without 0.01 mM *para*-nitroaniline (PNA). Conditions: UV irradiation at 2.2×10^{-7} Einstein·L^{-1}·s^{-1} with 0.3 mM H_2O_2 and 0.1 M $NaHCO_3$ in PBS. The irradiation time = 20 min. Error bars represent one standard deviation of the means (n = 2).

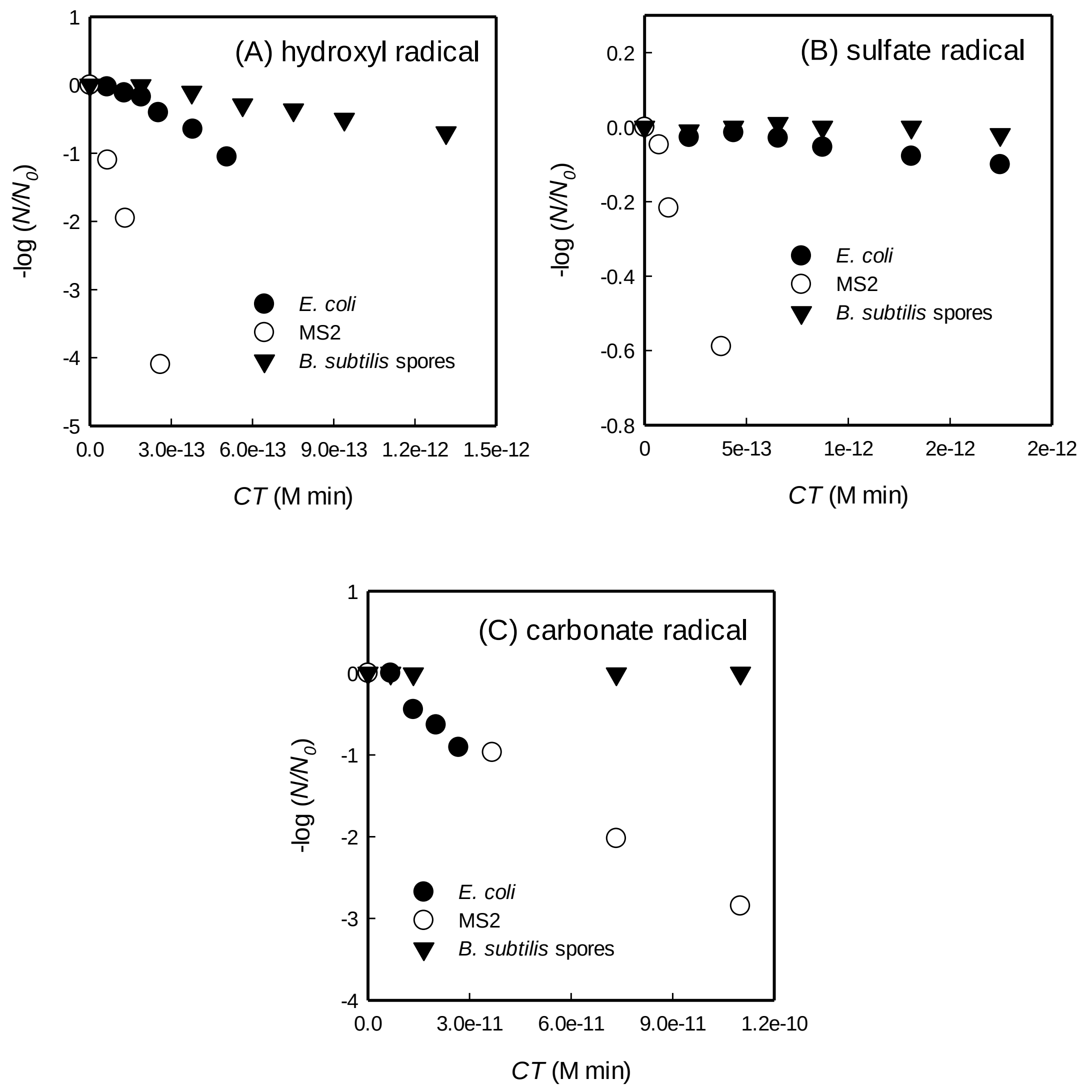

Figure S4. Inactivation of *E. coli*, bacteriophage MS2 and *Bacillus subtilis* spores versus *CT* values of (A) hydroxyl radical, (B) sulfate radical, and (C) carbonate radical.

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