Solar-based UV:
Fundamentals and applications

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Solar radiation spectrum

Sunlight at Top of the Atmosphere

5250°C Blackbody Spectrum

Radiation at Sea Level

Wikipedia
Solar vs lamp UV spectrum

- **UVC**
  - Low pressure

- **UVB**
  - Medium pressure

- **UVA**
  - Sunlight

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**Solar radiation**

**Solar UV mechanism**

**Example virus**

**Applications**

**Wrap-up**
Solar UV is less effective than UVC

Comparison of UVC (254 nm) and solar UV (300 nm):

- Energy UVC > solar UV (factor 1.2)
- Absorbance by genome of UVC >> solar UV (factor 125)

Need 150x higher intensity of solar UV for same effect
where we need 40 mJ/cm² UVC, we need 5000 mJ/cm² solar UV

\[ E = h \nu = hc/\lambda \]

- \( h \): Bolzmann constant
- \( c \): speed of light
- \( \lambda \): wavelength

Solar radiation
Solar UV mechanism
Example virus
Applications
Wrap-up
Solar UV intensity

Monthly Mean UVB intensity

Dependent on:
- season
- latitude
- weather
- elevation

In Delft (July): ca. 250 mJ/cm² solar UV per day

- 20 days of sun (5000 mJ/cm² solar UV) are as effective as UVC treatment (40 mJ/cm² UVC)

http://www.ufz.de/gluv
So why does solar UV disinfection work?

Solar UV acts by **three different mechanisms**:

**Direct inactivation:**
Absorption of UVB light by DNA/RNA
Genome damage

**Indirect endogenous inactivation:**
Absorption of UVB/UVA/(vis) light by *internal* sensitizers
Production of ROS and other transient species
Genome and protein damage

**Indirect exogenous inactivation:**
Absorption of UVB/UVA/(vis) light by *external* sensitizers
Production of ROS and other transient species
Genome and protein damage

ROS = reactive oxygen species
Formation of ROS and other transient species

Solar radiation

Solar UV

mechanism

Example virus

Applications

Wrap-up

Sens

Sens*

Energy transfer to $\text{O}_2$

94 kJ/mol (1260 nm)

Electron transfer to $\text{O}_2$

$t\text{O}_2$

$\text{O}_2^••$

e$^-$

$\text{H}_2\text{O}_2$

e$^-$

$\text{OH}^•$

Electron / energy transfer to other water constituents

$\text{CO}_3^•^-$, $\text{SO}_4^•^-$

Carbonate, sulfate
Some internal sensitizers absorb light at much higher wavelength than DNA, e.g.:
- Riboflavin
- Metalloproteins

*E. Coli* Inactivation occurs at wavelengths beyond UVB
External (exogenous) sensitizers

Natural organic matter (NOM)

One of many possible structures of NOM:
*Stevenson and Krasotinav, 1982*

Nitrite / nitrate

\[ \text{NO}_3^- \xrightarrow{h\nu} \text{NO}_3^- \rightarrow \text{NO}_2^- + \text{O}^- \rightarrow \text{NO}^- + \text{O}^- \rightarrow \text{HO}^- + \text{OH}^- \]
Which mechanism is important?

**Direct inactivation:**

*Important for:*
- All organisms

**Indirect endogenous inactivation:**

*Important for:*
- Bacteria
- maybe protozoa

*Less relevant for:*
- Viruses (no internal sensitizers)

**Indirect exogenous inactivation:**

*Important for:*
- Viruses
- Few bacteria

*Less relevant for:*
- Protozoa
- Spores
- Many other bacteria
Conceptual model for solar virus disinfection

**Direct**

\[ k_{\text{inact}} \approx \vartheta * P_a + k_{102}[^1O_2] + k_{\text{OH}}[\text{OH}^-] + k_{\text{NOM}*}[\text{NOM}*] + k_{\text{CO}_3^-}[\text{CO}_3^-] \] [1/time]

**Indirect**

Virus dependent

System dependent

Rate of light absorption \( P_a \): mols of photons absorbed by virus / time

Inactivation quantum yield \( \vartheta \): mols of infective virus inactivated / mols of photons absorbed by virus

Steady-state concentrations of ROS:

\( \frac{\text{mol ROS}}{L} \)

Second-order inactivation rate constant \( k \): \( \frac{1}{\text{ROS concentration} \times \text{time}} \)
Solar disinfection varies between viruses

Direct inactivation: phiX174 > MS2
Indirect inactivation: MS2 > phiX174

\[ k_{\text{inact}} \approx \varrho \cdot P_a + k_{1O2}[1O_2] + k_{\text{OH}}[\text{OH}^-] + k_{\text{NOM}^*}[\text{NOM}^*] + k_{\text{CO}_3^-}[\text{CO}_3^-] \]

\[ \varrho \] (mol pfu/mol photons)

\[ k \] (M⁻¹s⁻¹)

Mattle et al., submitted

- Direct inactivation: phiX174 > MS2
- Indirect inactivation: MS2 > phiX174
Modeled inactivation rates and main processes

Example diluted wastewater

MS2

phiX174

$k (1/SSD)$

$\text{depth (m)}$

$\text{depth (m)}$

Solar radiation
Solar UV mechanism
Example virus
Applications
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direct  OH•  $^{1}\text{O}_2$  NOM*
What happens to the virus?

Virus components

- Genome
- Protein
- Core proteins (V, VII and μ)
- Terminal protein
- Hexon protein
- Penton base
- Protease
- Fiber

Virus life cycle

- Attachment
- Entry
- Replication
- Release
What happens to the virus?

Direct (UV)

Indirect (\(^1\text{O}_2\))

Bosshard et al., AEM 2013
Solar disinfection of bacteria: conceptual model

It’s complicated....
Solar disinfection applications: low-tech

Application examples

![Wastewater treatment](https://www.rockymtnhouse.com)

![Drinking water treatment](https://todosupervivencia.com)

Wastewater treatment

Drinking water treatment
Solar disinfection applications: low-tech

Wastewater treatment

Anaerobic:
- BOD and SS removal
- Biogas formation

Facultative:
- BOD removal
- Some pathogen inactivation

Maturation:
- Pathogen inactivation and removal

High pathogen removal/inactivation!
- 6 log bacteria
- 4 log viruses
- 1 log protozoa
- 100 % helminth eggs

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Wastewater treatment

Dandora Pond, Kenya; 160,000 m³/day (2 Mio. Kenyans)

WSPs in Europe and US:

- Germany: 3000 ponds
- France: 2500 ponds
- US: 7500 ponds
Solar disinfection applications: low-tech

Drinking water treatment SODIS

Used by 5.8 million people in 30 countries
SODIS works best between 35°N and 35°S

- Use clean PET bottles
- Fill bottles with water, and close the cap
- Expose bottles to direct sunlight for at least 6 hours (or for two days under very cloudy conditions)
- Store water in the SODIS bottles
- Drink SODIS water directly from the bottles, or from clean cups
Solar disinfection applications: low-tech

Drinking water treatment SODIS

Optimal exposure times:
- 6 hours under up to 50% cloudy sky
- 2 days under 100% cloudy sky
- does not perform well during rain

Disinfection mechanisms:
- Heating of water
- Indirect inactivation
- BUT: no direct inactivation!

Performance:

<table>
<thead>
<tr>
<th>Pathogen</th>
<th>Reduction through SODIS ** at water temperatures of 40°C and solar exposure of 6 hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bakteria</td>
<td></td>
</tr>
<tr>
<td>E.coli</td>
<td>3-4 log (99.9 - 99.99%)</td>
</tr>
<tr>
<td>Vibrio cholera</td>
<td>3-4 log</td>
</tr>
<tr>
<td>Salmonella spp.</td>
<td>3-4 log</td>
</tr>
<tr>
<td>Shigella spp.</td>
<td>3-4 log</td>
</tr>
<tr>
<td>Viruses</td>
<td></td>
</tr>
<tr>
<td>Rotavirus</td>
<td>3-4 log</td>
</tr>
<tr>
<td>Polio Virus</td>
<td>inactivated, results not yet published</td>
</tr>
<tr>
<td>Hepatitis Virus</td>
<td>Reduction of cases of SODIS users</td>
</tr>
<tr>
<td>Protozoa</td>
<td></td>
</tr>
<tr>
<td>Giardia spp.</td>
<td>3-4 log (Infectivity of Cysts)</td>
</tr>
<tr>
<td>Cryptosporidium spp.</td>
<td>2-3 log (Infectivity of Cysts)</td>
</tr>
<tr>
<td>Entamoeba histolitica</td>
<td>trophohzoid stage inactivated</td>
</tr>
</tbody>
</table>

www.sodis.ch
Solar disinfection applications: low-tech

Drinking water treatment SODIS

**Advantages:**
- Reduces the risk of illness due to contaminated water by 50 -75 %
- Simple maintenance and handling
- Relies on locally available resources: PET bottles and sunlight
- Very low cost

**Disadvantages:**
- Not ideal for use by children
- Requires availability of PET bottles
- Some education necessary
- Not suitable for high-throughput treatment
- Only works if turbidity < 30 NTU

Educational SODIS theater performance
www.sodis.ch
Solar disinfection applications: high-tech

**Upconversion**

Sequential absorption of 2 photons leads to emission of shorter wavelength light

- Can make UVC from sunlight!

**Application example:**

Prevention of biofilm growth and disinfection of bacteria on surfaces


*Cates et al., Environ Sci Technol 2011*
Take-home messages

- Solar light «works»!
- Compared to UVC technology, solar UV is less effective, but it can penetrate deeper into the water column
- Sunlight inactivates pathogens by direct and indirect processes
- Their importance depends on the organism and the water composition (NOM!)
- Solar light is used for low-tech water treatment applications
- It is likely that we’ll see high-tech applications in the near future, too