SODIS Enhancement Technologies: Pilot testing for developing countries

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One-day symposium on
UV disinfection in developing countries
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UNESCO – IHE
Institute for Water Education
1. Central receiver technology
2. Parabolic dishes + Stirling engines
3. Parabolic-trough technology (thermal oil)
4. Parabolic-trough technology (DSG)
5. Parabolic-troughs (gas) + Molten Salt TES
6. Linear Fresnel Collector
7. Solar furnaces
8. Water desalination
9. Water purification
10. Energy Efficiency in Buildings
Solar reactors for water disinfection
Outlook

1. Sunlight for water disinfection
2. How to enhance solar water disinfection
3. Key parameters and solar reactors design
4. Experimental research and field studies
5. Concluding remarks
**Solar spectrum**

*Standard Solar Radiation Spectra*

- Extraterrestrial
- Global 37º Air Mass 1.5

**Irradiance, \( W \, m^{-2} \, \mu m^{-1} \)**

**Wavelength, \( \mu m \)**

**UV range**

**UV irradiance, \( W \, m^{-2} \, \mu m^{-1} \)**

**Wavelenght , \( \mu m \)**
Damages of UV radiation over cells

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Photons with wavelengths between $300 \text{ y } 500 \text{ nm}$ may inhibit reproduction capacity of microorganisms (1958). Photo-repair mechanisms of bacteria (not virus) is activated under similar range photons (1967).

**E. coli**

Natural sunlight (PSA) 
\(<\text{UVA}>=48 \text{ W m}^{-2}\)

20°C

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**Solar Water Disinfection efficacy**

Solar Water Disinfection efficacy

Solar Water Disinfection efficacy under natural sunlight

**The challenge: to improve SODIS**

**What is SODIS?**
Transparent containers are filled with contaminated water and placed in direct sunlight for at least 6 hours, after which time it is safe to drink.

**The positives:**
- Low cost, since usually only the poorest communities tend to be affected.
- Easy to use. Compliance will suffer if the protocol is overly complicated.
- Sustainable. The technique must not require consumables that are difficult or too expensive to obtain.

**The negatives:**
- Undesirable bacterial re-growth may occur.
- Some water pathogens are very resistant.
- Small water outputs and large treatment times.
- Strongly dependent on weather conditions.

55 countries where, in 2009, SODIS was in daily use by more than 4.5 million people (Meierhofer and Landolt, 2009).
The challenge: to improve SODIS

Water being treated by SODIS at a primary school in Southern Uganda. Students fill their bottles at home and expose them to the sun while they are in class (McGuigan et al., 2012).
New solar reactors for water disinfection should...

(i) maximize the collection of solar energy dose
(ii) enhance the disinfecting efficacy especially against resistant pathogens
(iii) increase the output of treated water in given solar exposure time
(iv) reduce the treatment time
(v) reduce the user dependence of the process
(vi) utilise cheap and robust disinfection systems, which may also be constructed with local materials without sophisticated technological needs (this is especially important for developing countries)
(vii) optimize photoreactor design taking into account the disinfection mechanisms and previous knowledge based on practical experiences on disinfection of real contaminated waters and wastewaters.
Disinfection parameters to be considered ...

- Dark inactivation superimposed to solar disinfection (SD) and solar photocatalytic disinfection (SPD)
- Reactor flow rate
- Intermittence and intensity of the radiation
- Water temperature
- Turbidity of the water
- Bacterial concentration
- Chemical composition of water (Ions, NOM, DOC)
- Nature and origin of biological contamination
Enhancement of Solar Water Disinfection

1. Water temperature increase
2. Solar UVA collection enhancement
3. Photochemical processes
4. New design concepts
Increasing Water temperature

25 litre in a CPC(20cm) within 8h

\[ \Delta T : 21^\circ C \text{ to } 58^\circ C \text{ (30NTU)} \]

\[ \Delta T : 21^\circ C \text{ to } 45^\circ C \text{ (0NTU)} \]
Increasing Water temperature

2.5 litre in a CPC(5cm) within 4h

$\Delta T : 20^\circ C$ to $42-52^\circ C$ (30NTU)

$\Delta T : 20^\circ C$ to $40-42^\circ C$ (0NTU)
Temperature of the water

Mild heat sensitivity of *E. coli* during SODIS (41-52°C). (Berney et al., 2006)

25l batch solar CPC reactor filled with well water.
Increasing Water temperature during disinfection

TiO₂/UVA disinfection of UWW

Photo-Fenton disinfection

Fig. 5 – E. faecalis inactivation by photo-Fenton process ($H_2O_2 = 120$ mg L⁻¹ and $Fe^{2+} = 10$ mg L⁻¹) at different temperatures: (▲) 10 °C; (●) 20 °C; (■) 30 °C; (△) 40 °C.
Enhancement of Solar Water Disinfection

Solar photocatalysis

\[ \text{TiO}_2 / \text{UVA (Carey et al., 1976)} \]

\[ \text{h} \cdot \nu \geq 3.2 \text{ eV} \]

\[ \text{TiO}_2 \xrightarrow{\text{hv}} \text{TiO}_2 (e^- + h^+) \]

\[ h^+ + H_2O \rightarrow \cdot OH + H^+ \]

\[ e^- + O_2 \rightarrow O_2^{--} \]

\[ \text{photo-oxidación} \]
TiO$_2$ photocatalytic inactivation of fungal spores

Pilot scale

CPC photo-reactor of 14 L

Enhancement of Solar Water Disinfection

Solar photo-oxidation

Fe(III)-Fe(II)/UVA

Aquacomplexes Fe(III) + hν → •OH
(Mazellier et al., 1997; Mailhot et al., 1999)

Aquacomplexes Fe(II) + hν → •OH
(Benkelberg and Warneck, 1995)

Fenton
(J. Chem. Soc., 1894)

\[ Fe^{2+} + H_2O_2 \rightarrow Fe^{3+} + OH^- + \cdot OH \]

Photo-Fenton
(several authors, early 90s)

\[ Fe^{3+} + H_2O \xrightarrow{hv} Fe^{2+} + H^+ + \cdot OH \]

H₂O₂/UVA

H₂O₂ + hν → 2•OH
(Several authors)

Internal photo-Fenton

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Comparison of three photo-chemical processes
H$_2$O$_2$/solar; Fe$^{3+}$/solar and Fe$^{3+}$/H$_2$O$_2$/solar

F. solani

Enhancement of Solar energy income
**Compound Parabolic Collectors: CPC**

\[
C = \frac{1}{\sin \theta_a}
\]

One Sun CPC collector manufacturing: \( \theta_a = 90^\circ \Rightarrow \) all direct and diffuse solar photons can be collected and used (diffuse UV radiation is a very important fraction of solar UV)
Ray tracing for CPC collectors
CPC enhancement

Concentration factor (CF)

\[ CF = \frac{Aperture\ area}{Absorber\ area} \]

CPC with CF=1

CPC with CF=1.89

Optic axis

CPC mirror

Aperture area

Absorber area

South

37°
CPC enhancement

CPC enhanced inactivation of *E. coli* under natural sunlight: clear and cloudy days using real well-water (batch systems)

Sunny vs. cloudy days

SODIS & TiO$_2$

**Sunny day (March 22$^{nd}$ 2006)**
- solar-only
- sunlight+TiO$_2$

**Cumulative UV dose**

Hourly average UV irradiance

- Max irradiance 42 Wm$^{-2}$
- UVA dose 750 kJm$^{-2}$

**Cloudy day (March 21$^{st}$ 2006)**
- solar-only
- sunlight+TiO$_2$

**Cumulative UV dose**

Hourly average UV irradiance

- Max irradiance 25 Wm$^{-2}$
- UVA dose 380 kJm$^{-2}$

*Sichel et al., Catalysis Today 129, 152-160, 2007*
Disinfection under solar light

Experimental time is used to compare results when lamps are used. When solar radiation drives the process, we can use the following evaluation parameters:

a) \( Q_{uv} \): cumulative UV energy during exposure time per unit of volume of treated water (J l\(^{-1}\)).

\[
Q_{uv,n} = Q_{uv,n-1} + UV_{G,n} \cdot \Delta t_n \cdot A/V_t
\]

b) **UV Dose**: UV energy received per unit surface during exposure time (J m\(^{-2}\)).

\[
Dose_{uv} = UV_{G,n} \cdot \Delta t_n
\]

c) **UV Energy**: total UV energy received during exposure time (J).

\[
Energy_{uv} = UV_{G,n} \cdot A \cdot \Delta t_n
\]
How is the solar energy delivered?

The concept design of reactors for solar water disinfection should be ‘static batch’ if the treatment times are long (> 20-30 min) or ‘continuous-flow systems’ with residence times equal to that required to receive the lethal UVA dose.

At a given time point there needs to be maximum exposure of bacteria to UV to ensure inactivation as compared with having bacteria exposed to sub-lethal doses over a long period of time.

Ubomba-Jaswa et al., Photobiol. Sciences, 8(5), 587-595, 2009

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It was observed that bacterial inactivation depends on UVA dose for UVA irradiance values between 14 and 40 W·m⁻². There is a minimum and uninterrupted UVA dose needed for a complete inactivation of bacteria; this dose was defined as the “uninterrupted lethal UVA dose”.

Ubomba-Jaswa et al., Photobiol. Sciences, 8(5), 587-595, 2009
Static batch reactors

CPC tube – 2.5 l

Length = 1.50 m

Diameter = 0.05 m

Sampling valve
Closed end

Glass tube
CPC reflector

25l CPC-SODIS batch reactor
Batch CPC SODIS reactor

Irradiated length: 92.5 cm
Irradiated width: 62.5 cm
Aperture area: 0.58 m²
External diameter of tube: 20 cm
Thickness of tube: 1 cm
Total volume: 25 L
Irradiated volume: 25 L

Batch SODIS reactors
Disinfection (E. coli) performance

Batch SODIS reactors

- Throughout the 7 month study period this reactor achieved 3 to 6 log reduction in bacteria concentration in natural well-water.
- Sunny conditions: bacteria were completely eliminated within 5 h.
- When water temperatures exceeded 45ºC, complete inactivation was achieved in highly turbid water (100 NTU) within 7 h.
- On cloudy days, 5 h solar exposure was sufficient to decrease bacterial population by 3 logs.
- It is therefore recommended that water be exposed for 2 days under cloudy conditions.

Batch SODIS reactors
Disinfection (C. parvum) performance

Disinfection performance for several types of water - Batch SODIS (CPC-25l)

\[ E. \text{coli (CFU mL}^{-1}) \]

\[ \text{Dose}_{uv} \text{ (kJ m}^{-2}) \]

Distilled water
Well water
Simulated WWTP
Real WWTP

Enhancement disinfection performance with H$_2$O$_2$ - Batch SODIS (CPC-25l)


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The objective is to develop a SODIS reactor that …
- decreases the treatment time required
- increases the total volume of water treated per day
- reduces user dependency

1. Automated system, **controlled by UVA feedback sensors**, for the solar disinfection of drinking water:
2. It incorporates a CPC with a concentration factor of 1.89 which decreases by half the exposure time to disinfect *E. coli* in well water.
3. It ensures that a predetermined UVA dose is received by the water and provides some level of water quality assurance.

Sequential batch reactor


- CPC reflector
- Electronic dosimetric control system
- Borosilicate tube
- Storage tank with treated water
- Platform titled 37°C
Sequential batch reactor

Solar uninterrupted UVA dose applied:

- **30 Wh/m²**
- **68 Wh/m²**

Total treatment time = 2.5 h

Total treatment time = 1 h

*CPC 1.9*

Recirculated batch reactors
SOLWATER & AQUACAT prototype

Concept of the final system (25L)

1. PV panel
2. Photo-reactor with Ru(II)
3. Photo-reactor with TiO₂
4. Pump
5. Electric box
6. Connections


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SOLWATER & AQUACAT prototype

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Solar flow reactors for real WW effluents disinfection

**Solar radiation**

- **Concentration (CFU or PFU/100niL)** vs. **Local Time (HH:MM)**
  - Values range from $10^1$ to $10^5$

**P25 (100 mg L$^{-1}$) + solar**

- **Concentration (CFU or PFU/100mL)** vs. **Local Time (HH:MM)**
  - Values range from $10^1$ to $10^5$

**Photo – Fenton pH3**

- Concentration (CFU or PFU/100mL) vs. **Time (HH:mm)**
- Values range from $10^1$ to $10^5$

**Photo-Fenton at natural pH (8)**

- Concentration (CFU or PFU/100mL) vs. **Time (HH:mm)**
- Values range from $10^1$ to $10^5$

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*Escherichia coli* (■■■)  
*SRC*: Sulphite reducing clostridia (▼▼▼)  
*SOMCPH*: somatic coliphages (●●●)  
*FRNA*: F specific RNA bacteriophages infecting *Salmonella* strain WG49 (▲▲▲)  

*Agulló-Barceló et al., 2013.*
CPC reactor in Kenya
Conclusions

• Critical importance of evaluating the parameters such as flow rate, total volume of water, temperature, and solar energy when attempting the task of up-scaling SODIS, particularly when large reactors are proposed.

• Characterizing the uninterrupted solar UVA dose required for inactivation of specific microorganisms must be incorporated into the design SODIS reactors.

• The CPC has been proven as a SODIS enhancement technology, allowing more radiation to reach the absorbing volume leading to a reduction in the SODIS exposure time and allowing the treatment of higher volumes of water on the same day.

• Significant disinfection can be achieved using a low cost CPC enhanced 25 L batch SODIS reactor.
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Thanks for your attention. Questions?

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