Waste water treatment by advanced oxidation processes (solar photocatalysis in degradation of industrial contaminants)

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Plataforma Solar de Almería, TABERNAS-Almería
SPAIN

Outlook

Introduction
Photocatalysis
Photo-Fenton

Photoreactors
Compound Parabolic Collectors
State of the art

Applications
Pesticides
OMW
Pharmaceutical WW
**Introduction**

Biodegradable substances:
- Biofilter treatment/ activated sludge treatment

Non-biodegradable substances can show:
- Non-toxic / inert behaviour
- Acute toxicity
- Chronic toxicity

**Alternative treatment**

**Incineration**
- High costs
- Toxic by-products
- High energy consumption

**Activated carbon Air stripping**
- Partial destruction

**Bio-treatment**
- High costs
- High energy consumption
- OH radicals

**Ozone**
- Incineration
- Bio-treatment
Introduction

Photochemical AOPs

<table>
<thead>
<tr>
<th>AOP</th>
<th>key reactions</th>
<th>wavelength</th>
</tr>
</thead>
<tbody>
<tr>
<td>UV/H₂O₂</td>
<td>H₂O₂ + hv → 2 OH⁺</td>
<td>λ &lt; 300 nm</td>
</tr>
<tr>
<td>UV/O₃</td>
<td>O₃ + hv → O₂ + O (1D)</td>
<td>λ &lt; 310 nm</td>
</tr>
<tr>
<td></td>
<td>O (1D) + H₂O → 2 OH⁺</td>
<td></td>
</tr>
<tr>
<td>UV/H₂O₂/O₃</td>
<td>O₃ + H₂O₂ + hv → O₂ + OH⁺ + OH⁻⁺</td>
<td>λ &lt; 310 nm</td>
</tr>
<tr>
<td>UV/TiO₂</td>
<td>TiO₂ + hv → TiO₂(e⁺ + h⁻)</td>
<td>λ &lt; 390 nm</td>
</tr>
<tr>
<td></td>
<td>TiO₂(e⁺ + h⁻) + OH⁻ → TiO₂ + OH⁻⁺</td>
<td></td>
</tr>
<tr>
<td>photo-Fenton</td>
<td>H₂O₂ + Fe²⁺ → Fe³⁺ + OH⁻ + OH⁻⁺</td>
<td>λ &lt; 580 nm</td>
</tr>
<tr>
<td></td>
<td>Fe³⁺ + H₂O + hv → Fe²⁺ + H⁺ + OH⁻⁺</td>
<td></td>
</tr>
</tbody>
</table>
Photocatalysis

Standard Solar Radiation Spectra

Extraterrestrial

Global 37° Air Mass 1.5

\[ U = \frac{hc}{\lambda} \]

Material “Band gap” (eV) \( \lambda \) for e-/h+ formation (nm)

<table>
<thead>
<tr>
<th>Material</th>
<th>“Band gap” (eV)</th>
<th>( \lambda ) (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CdO</td>
<td>2.1</td>
<td>590</td>
</tr>
<tr>
<td>Cds</td>
<td>2.5</td>
<td>497</td>
</tr>
<tr>
<td>Fe2O3</td>
<td>2.2</td>
<td>565</td>
</tr>
<tr>
<td>GaP</td>
<td>2.3</td>
<td>540</td>
</tr>
<tr>
<td>SnO2</td>
<td>3.9</td>
<td>318</td>
</tr>
<tr>
<td>TiO2</td>
<td>3.0</td>
<td>390</td>
</tr>
<tr>
<td>WO3</td>
<td>2.8</td>
<td>443</td>
</tr>
<tr>
<td>ZnO</td>
<td>3.2</td>
<td>390</td>
</tr>
<tr>
<td>ZnS</td>
<td>3.7</td>
<td>336</td>
</tr>
</tbody>
</table>

Photocatalysis

“band gap” energy is the energetic separation between a semiconductor valence and conduction band

\[ \lambda_G = \frac{hc}{E_G} \]

C + h\nu \rightarrow C(e^- + h^+)  

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

\[ e^- + O_2 \rightarrow O_2^- \]
The process takes place at ambient temperature.

Oxidation of the substances into CO$_2$ is complete.

The oxygen necessary for the reaction is obtained from the atmosphere.

The catalyst is cheap, innocuous and can be reused.

The catalyst can be attached to different types of inert matrices.
**Photo-Fenton**

**Photo-Fenton method**

\[
\begin{align*}
\text{Fe}^{2+} + H_2O_2 & \rightarrow \text{Fe}^{3+} + OH^- + \bullet OH \\
\text{Fe}^{3+} + H_2O & \xrightarrow{hv} \text{Fe}^{2+} + H^+ + \bullet OH
\end{align*}
\]

**Advantages**
- High reaction rates
- Cheap, non-toxic reagents (Fe, H_2O_2, acid, base)

**Disadvantages**
- pH adjustment necessary
- Iron removal necessary

---

**Reactions Fe^{2+}, Fe^{3+} and H_2O_2 in water**

**Radical reactions**

\[
\begin{align*}
\text{Fe}^{2+} + \text{H}_2\text{O}_2 & \rightarrow \text{Fe}^{3+} + \text{OH}^- + \bullet \text{OH} \\
\text{Fe}^{3+} + \text{OH}^- & \rightarrow \text{Fe}^{2+} + \text{OH}\bullet \\
\text{Fe}^{2+} + \text{H}_2\text{O}_2 & \rightarrow \text{Fe}^{3+} + \text{H}^+ + \bullet \text{OH} \\
\text{Fe}^{3+} + \text{H}_2\text{O}_2 & \rightarrow \text{Fe}^{2+} + \text{O}_2 + \text{H}^+ \\
\text{Fe}^{3+} + \text{OH}^- & \rightarrow \text{Fe}^{2+} + \text{O}_2 \\
\text{OH}^- + \text{H}_2\text{O}_2 & \rightarrow \text{H}_2\text{O}_2 + \text{HO}_2^- \\
\end{align*}
\]

**Equilibriums**

\[
\begin{align*}
2\text{OH}^- & \rightarrow \text{H}_2\text{O}_2 \\
\text{HO}_2^- + \text{H}_2\text{O}_2 & \rightarrow \text{H}_2\text{O}_2 + \text{HO}_2^- \\
\text{HO}_2^- & \rightarrow \text{HO}_2^- + \text{H}^+ \\
\text{HO}_2^- + \text{H}^+ & \rightarrow \text{H}_2\text{O}_2 + \text{H}^+ \\
\end{align*}
\]

**Kinetic constants**

\[
\begin{align*}
k &= 3.55 \times 10^{12} \text{ M}^{-1} \text{s}^{-1} \\
K &= 3 \times 10^{-12} \text{ M} \\
K &= 2.60 \times 10^{-12} \text{ M} \\
K &= 3.16 \times 10^{-12} \text{ M} \\
K &= 3.98 \times 10^{-12} \text{ M} \\
K &= 5.00 \times 10^{-12} \text{ M} \\
K &= 6.50 \times 10^{-12} \text{ M} \\
K &= 7.50 \times 10^{-12} \text{ M} \\
K &= 8.50 \times 10^{-12} \text{ M} \\
K &= 1.50 \times 10^{-12} \text{ M} \\
K &= 3.50 \times 10^{-12} \text{ M} \\
K &= 5.50 \times 10^{-12} \text{ M} \\
K &= 9.50 \times 10^{-12} \text{ M} \\
K &= 1.20 \times 10^{-12} \text{ M} \\
K &= 1.90 \times 10^{-12} \text{ M} \\
K &= 3.00 \times 10^{-12} \text{ M} \\
K &= 5.10 \times 10^{-12} \text{ M} \\
K &= 3.10 \times 10^{-12} \text{ M} \\
K &= 2.60 \times 10^{-12} \text{ M} \\
K &= 3.10 \times 10^{-12} \text{ M} \\
K &= 3.10 \times 10^{-12} \text{ M} \\
K &= 3.10 \times 10^{-12} \text{ M} \\
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K &= 3.10 \times 10^{-12} \text{ M} \\
K &= 3.10 \times 10^{-12} \text{ M} \\
\end{align*}
\]
**Photo-Fenton**

**Fenton reactions with organics**

- \( R^+ + \text{Fe}^{2+} \rightarrow R^- + \text{Fe}^{3+} \)
- \( R^- + \text{Fe}^{3+} \rightarrow R^- + \text{Fe}^{2+} \)
- \( R^- + R^+ \rightarrow R + R^- \)
- \( \text{R}^+ + \text{HO}_2^- \rightarrow \text{RO}_2^- \)
- \( \text{Fe}^{3+} + \text{RO}_2^- \rightarrow \text{Fe}^{2+} + \text{OH}^- + \text{OR}^- \)
- \( \text{R}^+ + \text{O}_2 \rightarrow \text{RO}_2^- \)
- \( \text{RO}_2^- + \text{H}_2\text{O} \rightarrow \text{ROH} + \text{HO}_2^- \)

Persistent complexes with Mono- and Dicarboxylic acids (L).

Reactions is stopped before complete mineralisation

\[
\text{Fe}^{3+} + n \text{L} \rightarrow \left[ \text{FeL}_n \right]^{x+} + \frac{1}{2} \text{H}_2\text{O}_2, \text{dark} \rightarrow \text{no further reaction}
\]
Photo-Fenton

Source: Scopus (http://www.scopus.com), June 2007

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- Pharmaceutical WW
Photoreactors

Innovative Processes and Practices for Wastewater Treatment and Reuse. 8-11 October 2007, Ankara University, Turkey

Batch process

Pump → Filter → Mixer → Tank → Contaminated water → Oxygen (Air) → Sun → Solar UV light → Photoreactor (Solar Collector Field) → Chemical oxidant → Catalyst → Pre-treatment (pH adjustment, filtering, etc.) → Post-treatment (catalyst recovering, pH adjustment, etc.) → Treated water → Treated water
**Photoreactors**

Reflectivity (%)

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Reflectivity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>320</td>
</tr>
<tr>
<td>340</td>
<td>360</td>
</tr>
<tr>
<td>380</td>
<td>400</td>
</tr>
</tbody>
</table>

Transmissivity (%)

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Transmissivity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
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</tr>
<tr>
<td>340</td>
<td>360</td>
</tr>
<tr>
<td>380</td>
<td>400</td>
</tr>
</tbody>
</table>

**Photoreactors**

- **Direct radiation**: solar radiation that reaches ground level without being absorbed or scattered.
- **Diffuse radiation**: the radiation that has been dispersed but reaches the ground.
- **Global radiation**: The sum of both.

---

**Solar UV Spectra**

- **UV direct (tracking the Sun)**
- **UV global horizontal**
Photoreactors

UV must be accurately measured!

Maximum UV (λ<400 nm) sunny days (37°, N)
Sandia National Labs (Albuquerque, USA) developed in 1989 the first solar facility for water detoxification at pre-industrial level based on 1-axis Parabolic Trough Collectors (PTC). CIEMAT, in 1990, erected the second at Plataforma Solar de Almería (Spain), using 2-axis PTCs.

These pilot plants were the first step in the development of the solar technology.

In the early nineties, the National Renewable Energy Laboratory, Sandia National Laboratories and the Lawrence Livermore National Laboratory addressed the “Livermore experiment” (USA). A Solar Detox Plant was installed using one-axis PTCs to treat TCE-groundwater contaminated during the Second World War. This experiment constituted the first on-site test. Tests were successful but the economic figures not!
One-sun (non-concentrating) collectors are cheaper than PTCs. An extensive effort in the design of small non-tracking collectors, has resulted in the testing of several different non-concentrating solar reactors.

The design of a robust one-sun photoreactor is not trivial: weather-resistant, chemically inert and ultraviolet-transmissive. Also, flow in non-concentrating systems is usually laminar.
DSSR-Pilotplant II

The Planning Concept:

- Illuminated Reactor Area \( A = 30 \text{ m}^2 \)
- Flow \( Re = 5000 \) (turbulent)
- Volumetric Flow Rate \( V_{\text{tot}} = 12 \text{ m}^3/\text{h} \)
- Pressure Drop = 0.5 bar
- Treatment Capacity 0.9 m\(^3\)/d

DSSR-Pilotplant II in Wolfsburg

Source: Prof. D. Bahnemann, Universität Hannover
Thin-Film Fixed Bed Reactor (TFFBR)

Source: Prof. D. Bahnemann, Universität Hannover

State of the art

1995 in Almeria/Spain
2003 in Tunis/Tunisia

Source: Prof. D. Bahnemann, Universität Hannover
### State of the art

<table>
<thead>
<tr>
<th>PARABOLIC CONCENTRATORS</th>
<th>MAIN ADVANTAGES</th>
<th>MAIN DISADVANTAGES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbulent flow</td>
<td>Direct radiation</td>
<td>Only Direct radiation</td>
</tr>
<tr>
<td>No vaporization of compounds</td>
<td>Laminar flow (low mass transfer)</td>
<td>High cost (Sun Tracking)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Low optical efficiency</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Low Quantum efficiency (with TiO₂)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Overheating</td>
</tr>
</tbody>
</table>

### MAIN ADVANTAGES

- High optical efficiency
- No tracking
- No Overheating
- Direct and Diffuse radiation
- Low cost
- Weatherproof (no contamination)

### NON CONCENTRATING PHOTOREACTORS

<table>
<thead>
<tr>
<th>MAIN ADVANTAGES</th>
<th>MAIN DISADVANTAGES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct &amp; Diffuse radiation</td>
<td>Laminar flow (low mass transfer)</td>
</tr>
<tr>
<td>No heating</td>
<td>Vaporization of reactants</td>
</tr>
<tr>
<td>Low cost</td>
<td>Reactants contamination</td>
</tr>
</tbody>
</table>

### Compound Parabolic Collectors

- 1 Sun COMPOUND PARABOLIC COLLECTORS
  - Turbulent flow conditions
  - No vaporization of volatile compounds
  - No tracking
  - No Overheating
  - Direct and Diffuse radiation
  - Low cost
  - Weatherproof (no contamination)
Compound Parabolic Collectors

\[ C = \frac{I}{\sin \theta} \]

\[ \rho = r \theta \quad \text{for} \quad |\theta - \theta_0 + \pi/2| \]

\[ \rho = r \frac{\theta + \pi/2 - \cos(\theta - \theta_0)}{1 + \sin(\theta - \theta_0)} \quad \text{for} \quad \theta, + \frac{\pi}{2} < |\theta - \theta_0|/2, \]

Part A-B

Part B-C

If \( \theta_0 = 90^\circ \Rightarrow C = 1 \)

One Sun CPC collector manufacturing: \( \theta_0 = 90^\circ \Rightarrow \) all direct and diffuse solar photons can be collected and used (diffuse UV radiation is a very important fraction of total solar UV).
A very simple one-sun CPC collector was designed, constructed and tested to optimize the manufacturing process (modularity), on-site installation (minimum interconnecting pieces and non-illuminating zones) and cost saving.

Additional system advantages:
- Easy manufacturing
- Low investment cost
- Simple operation and supervision
- Low maintenance requirements
- No sun tracking devices are needed
- UV diffuse radiation can be profited
Slurry systems are the most efficient, resulting in an important reduction in the final treatment cost. A process for catalyst recuperation has been patented. EP-1-101-737-A1 (2001).

The plant is designed with full automatic systems. A Programmable Logic Controller receives all plant data signals (flow-rate, tanks level, temp, solar UV-A irradiation, etc) and control pumps and system valves.

Process evolution is monitored through the measuring and integration of UV light up to a fixed level.
The SOLARDETOX Consortium (Brite-Euram III Program, Contract No. BRPR-CT97-0424) has installed during 1999 the first European Solar Detoxification Plant. Main plant characteristics are:

- CPC surface: 100 m²
- Treatment volume: 800 L
- Batch Operation
- Automatic operation
- Cost of the plant: 100000 €
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Applications

1976
- PHOTOCATALYSIS AT LAB SCALE (BASIC RESEARCH)

2007
- PHOTOCATALYSIS
- PILOT PLANT PHOTOCATALYSIS
- SOLAR COLLECTORS DEVELOPMENT
- NEW ENVIRONMENTAL EU DIRECTIVES: IPPC (1996), WFD (2000),...

NEW RESEARCH GROUPS
- NEW PROCESSES (catalysts, oxidants, photo-Fenton, ...)

TOO EXPENSIVE ALTERNATIVES:
- GAC, AIR STRIPPING, INCINERATION...

ENVIRONMENTAL MARKETING
- PRIVATE COMPANIES
It has demonstrated that the solar photocatalytic technology is sufficiently developed for industrial use. A European industrial consortium has been created to design and setup of turnkey SOLARDETOX plants.

The technology developed can be used, without modification, to address solar Photo-Fenton and TiO₂ degradation process.

APPLICATIONS
- Organics concentration ≤ hundreds of mg L⁻¹.
- Low-medium flow (< 10 m³/h).
- Contaminants present within complex mixtures of organics.
- Contaminants with no easy treatment by conventional technologies.

Applications
- Phenols, nitrophenols and halophenols.
- Pharmaceutical compounds (antibiotics, disinfectants...).
- Water disinfection.
- Gasoline additives (MTBE, ETBE,..).
- Chlorinated hydrocarbons (solvents, VOCs, etc).
- Residues from textile industry (dyes).
- Agrochemical wastes (pesticides).
Small amounts of pesticide remaining in the empty containers (approx. 70 units/ha).

1. The initial pesticide concentration can be controlled as a function, so the most appropriate concentration for optimum photocatalytic efficiency can be chosen.

2. Toxicity is extreme, low-volume and in a well-defined location.

3. Such point sources of pollution may be ideally treated in small-scale treatment units.

4. Intensive agriculture in greenhouses is usually concentrated in sunny countries.

QUITE WELL SUITED TO SOLAR PHOTOCATALYTIC TREATMENT:

1. The initial pesticide concentration can be controlled as a function, so the most appropriate concentration for optimum photocatalytic efficiency can be chosen.

2. Toxicity is extreme, low-volume and in a well-defined location.

3. Such point sources of pollution may be ideally treated in small-scale treatment units.

4. Intensive agriculture in greenhouses is usually concentrated in sunny countries.
The intensive agriculture activity is a very important economical sector in Almería. There are more than 350 km² of greenhouses.

These greenhouses yearly consume 5,200 tons of phytosanitary products (1.5 million of bottles; 1.9 L average volume).

A process has been designed to recycle the plastic of these bottles. The recycling process needs a washing of the plastic. This produces a water with hundreds of mg/L of persistent toxic compounds.

**Proposed Solution:** Solar Photocatalytic Treatment
Plant design data:

a) Total yearly volume of water to be treated ($V_t$): 1875 m$^3$

b) Yearly operating hours of solar facility ($T_s$): 3000 h

c) Yearly average global UV irradiation ($I_{UV}$), sunrise to sunset: 18.6 W$_{UV}$ m$^{-2}$

d) Average solar energy needed to degrade the contaminants ($Q_{UV}$): 12 kJ$_{UV}$ L$^{-1}$

Pesticides
Innovative Processes and Practices for Wastewater Treatment and Reuse.
8-11 October 2007, Ankara University, Turkey

Pesticides

Solar field figures:

a) Individual CPC modules formed by 20 parallel tubes (surface: 2.7 m²/module)

b) 4 parallel rows with 14 modules each mounted on a 37º-tilted platform (local latitude)

c) total collectors surface: 150 m²

d) Total photoreactor volume: 1061 L

e) Total volume per batch: 1500 to 2000 L

Final selected plant dimensioning (solar collector area) was: 150 m²

$$A_p = \frac{Q_s, V_s}{T, U/V} = \frac{12 \times 10^3 \times 1875 \times 10^3}{3000 \times 3600 \times 18.6} \text{x m}^{-2} \text{L} = 112 \text{m}^2$$
Operating procedure:

a) The system is run in batch mode using a 2000 L recirculation tank.

b) The 4 rows are connected in parallel (independently operated) and the 14 modules of each row in series.

c) After treatment water is returned to the washing system and the tank is refilled with new contaminated water.

Typical composition (only main parameters) of OMW:

- **COD**: 80000 mg/L
- **Dissolved Phenols**: 4500 mg/L
- **TOC**: 35000 mg/L
- **pH**: 5.1
- **Relevant anions**: phosphate 700 mg/L, chloride 500 mg/L, sulphate 100 mg/L, nitrite 6 mg/L.

Transmission spectra of OMW through 2 mm pathlength at different dilution ratios.
OMW Dissolved Phenols behaviour with different photocatalytic treatments

- Only TiO₂
- TiO₂ + S₂O₈⁻² 20 mM
- Fe 1mM + H₂O₂ 20 g/L
- Fe 5mM + H₂O₂ 20 g/L
- Fe 1mM + H₂O₂ 5 g/L

Dissolved Phenols (mg/L)

Q (kJ/L)

W=14.1 h
OMW

Installed and tested in a Olive Mill at Kivery (ARGOS, Greece).

OMW

Treatment of OMW in the FFR. Fe = 5mM

20 h-sunny days-March

COD and TOC (g/L)

Phenols

H₂O₂

Q (kJ/L)
Pot experiment performed in greenhouse because of:
- Protection from environment (wind, rain, insects)
- Controlled irrigation
- Additional light
Substrate:

Earth
- Bacteria ⇒ conversion of TOC
- Unknown disposal of nutrients

Perlita
- Aluminium silicate, porosity of 95%
- Inert substrate

Pots:
- 12 L volume, PVC, fair grey
### Composition of wastewater (seawater) containing Femac ($\alpha$-methylphenylglycine, C$_9$H$_{11}$NO$_2$)

<table>
<thead>
<tr>
<th>Component</th>
<th>mg L$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Femac</td>
<td>500-600</td>
</tr>
<tr>
<td>Susp. solids</td>
<td>20-100</td>
</tr>
<tr>
<td>COD</td>
<td>1500-1800</td>
</tr>
<tr>
<td>TOC</td>
<td>400-500</td>
</tr>
<tr>
<td>NH$_4^+$</td>
<td>0-40</td>
</tr>
<tr>
<td>NO$_3^-$</td>
<td>200-600</td>
</tr>
</tbody>
</table>

**Diagram:**
- Installed at DSM-DERETIL Villaricos (ALMERIA)
**Pharmaceutical WW**

- 1000+400 L contact column, 5 - 10 h of contact → Continuous flow 140 - 280 L·h⁻¹
- 700 L IBR
- 1260 L illuminated volume
- 4000 L total volume
- Recirc. Flow 11 m³·h⁻¹
- Continuous flow 40-80 L·h⁻¹

---

**Pharmaceutical WW**

- 1260 L illuminated volume
- 4000 L total volume
- Recirculation flow 1.2 m³·h⁻¹
- Continuous flow 40-80 L·h⁻¹
IBR during 75 days of continuous mode operation. Continuous operation showed the stability and permanent activity of the immobilised biomass with an influent, which originates from the AOP pre-treatment (photo-Fenton).

Overview coupling Photo-Fenton/Biotreatment
Innovative Processes and Practices for Wastewater Treatment
and Re-Use.
8-11 October 2007, Ankara University, Turkey

### Total cost per m³ of treated effluents containing 1 kg/m³ of Femac (i.e. 700 mg TOC/L) for different scenarios.

**Depreciation: 10 years**

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Reagents</th>
<th>Electric power</th>
<th>Manpower</th>
<th>Capital costs (solar field)</th>
<th>Capital costs (others)</th>
<th>Total (€ m⁻³)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>photo-Fenton/Biol (Demo plant)</strong></td>
<td>4.26 €/m³</td>
<td>0.43 €/m³</td>
<td>0.36 €/m³</td>
<td>1.96 €/m³</td>
<td>5.43 €/m³</td>
<td><strong>29.2€/m³</strong></td>
</tr>
<tr>
<td><strong>photo-Fenton/Biol (1000 m² CPC)</strong></td>
<td>4.26 €/m³</td>
<td>0.21 €/m³</td>
<td>0.21 €/m³</td>
<td>1.52 €/m³</td>
<td>0.89 €/m³</td>
<td><strong>10.4€/m³</strong></td>
</tr>
<tr>
<td><strong>photo-Fenton/Biol (10000 m² CPC)</strong></td>
<td>4.26 €/m³</td>
<td>2.00 €/m³</td>
<td>2.00 €/m³</td>
<td>1.52 €/m³</td>
<td>0.89 €/m³</td>
<td><strong>7.2€/m³</strong></td>
</tr>
</tbody>
</table>

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SPECIAL ISSUES ABOUT SOLAR PHOTOCATALYSIS