

# Developing solar cells with recycled materials and household chemicals for drinking water chlorination by communities with limited resources

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## Abstract

Ferric tannate-sensitized  $n$ -(ZnO, SnO<sub>2</sub>)/Cu photoelectrochemical cells were constructed for drinking water chlorination using recycled waste materials and household chemicals and utilising Fe<sup>2+</sup>–Fe<sup>3+</sup> and Cu<sup>2+</sup>–Cu redox couples for charge transfer. The solar cells, which were constructed in recycled clear plastic tubing and drinking straws in a home environment, produced an open-circuit voltages of 0.4–0.6 V and a short-circuit current densities of 1–2.5 mA cm<sup>-2</sup>. Chlorine was produced at a rate of 4 mg h<sup>-1</sup> from a 1% salt solution using an array of cells with a combined voltage of 5 V and a current of 200 mA. This study has demonstrated that it is possible to construct viable solar cells for drinking water chlorination using waste materials and readily available chemicals. Further studies are needed to determine how practicable this would be in regions with drinking water quality and sanitation problems.

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## 1. Introduction

A large amount of the current research and development of new solar technologies is focussed on achieving highly efficient systems that could generate electric power at costs that are competitive with fossil fuels and other energy sources. As a consequence, increasingly sophisticated manufacturing techniques and materials are being used in the development of new solar energy systems that are largely inaccessible in many parts of the world outside of specialised research institutions.

Although this work is extremely important and will hopefully eventually reduce global environmental problems caused by urban gas emissions, one immediate adverse con-

sequence of the current research focus is that solar energy is not playing a significant role in reducing the suffering and loss of life caused by unsafe drinking water in many parts of the world.

The world is currently experiencing a humanitarian crisis which is largely unrecognised in high-income countries. Currently about 1.1 billion people do not have access to a safe drinking water source within reasonable walking distance of their homes, and this factor combined with poor sanitation and inadequate hygiene practices is causing about 1.6 million deaths each year (Bartram et al., 2005). For each death, many more people become seriously ill, particularly children who bear much of the burden of diarrhoeal and other water-related diseases throughout the world (Howard and Bartram, 2005). These health problems are being exacerbated by squalid and overcrowded living conditions in urban slums as increasing numbers of people

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move from rural areas to seek a better life in large cities (Moore et al., 2003). Currently about half of the world's population live in urban areas, and this proportion is expected to rise to about 65% in 2015 (Moore et al., 2003).

The World Health Organisation (WHO) has set the Millennium Development Goal (MDG) target of reducing the proportion of people in the world without sustainable access to safe drinking water and sanitation by half by 2015. A large part of the challenge of this particular MDG is in the word “sustainable”. If this MDG is to be achieved, many communities will need to progressively become more self-reliant and less dependent on external help to manage water sources for potable use, and they will need access to a range of tools and information to help them do this.

The management of many small community or single household water supplies could remain problematic because of the difficulty of disinfecting drinking water using locally available resources. In many regions it may not be possible to obtain enough firewood to boil water because of the effects of deforestation and land degradation. Additionally, many local communities only have limited access to imported chlorination agents for water disinfection which greatly increases the risk of infection by waterborne diseases. Although drinking water can be thermally disinfected using simple solar methods such as the use of cardboard solar box cookers (Ciochetti and Metcalf, 1983) or allowing water to heat in clear plastic bottles (Conroy et al., 2000; Reed, 2004) the treatment rate is limited by the high specific heat of water.

These problems could be at least partially alleviated if sufficient electricity was made available in regions with unsafe drinking water to generate chlorine for disinfection by the electrolysis of saline water. The amount of energy required to do this would be extremely modest by comparison with typical household usage of electricity in high-income countries, and in many cases could be provided by solar power. Brine electrolysis could also enable excess chlorine to be stored in the form of sodium hypochlorite solutions or solid calcium hypochlorite which could either be traded or utilised if adverse weather conditions limited the rate of production of chlorine.

One possible way of increasing the uptake of solar chlorine production would be for communities to be trained in how to construct practicable solar cells themselves using locally available resources. If this were possible, it is likely that (appropriately supported) local enterprises and social networks could distribute the technology far more efficiently than would be possible by external aid agencies acting independently.

This paper outlines the first steps in the process of testing the feasibility of developing and constructing solar cells in a household setting constrained by a limited range of tools and using waste materials and natural products wherever possible. As a result of this work, a dye-sensitized  $n$ -(ZnO, SnO<sub>2</sub>)/Cu photoelectrochemical cell was developed utilising Fe<sup>2+</sup>–Fe<sup>3+</sup> and Cu<sup>2+</sup>–Cu redox couples for charge transfer (Licht, 2002) that is capable of producing enough

electricity in an array to chlorinate small amounts of drinking water.

## 2. Constraints and opportunities for constructing solar cells for drinking water chlorination in regions with drinking water quality and sanitation problems

It will only be viable to construct solar cells in regions with water quality and sanitation problems if the current paradigm of only selecting technologies on the basis of cost, efficiency of energy conversion and the shortness of their “payback” times is reconsidered in these regions. Although low-cost will continue to be important, under conditions of poor public health and widespread impoverishment factors such as availability of raw materials and ease of construction are likely to be more important considerations than the overall efficiency of the system. Under these conditions, “payback” could be assessed on the basis of whether the resources and labour invested in constructing solar cells are warranted, and whether more drinking water could be disinfected by utilising the raw materials in other ways (for example, by constructing a short-lived galvanic battery with metallic components for brine electrolysis).

The limited availability of raw materials and lack of access to specialised construction technologies are likely to constrain the range of solar technologies that could be locally constructed in regions with water quality and sanitation problems. These factors would generally make it impractical to construct conventional solid-state solar cells in these regions. Photoelectrochemical cells are likely to be much easier to construct and use under these conditions.

One of the most important sources of construction materials for solar cells in regions with drinking water problems is likely to be waste streams in large urban centres in these regions. Ironically, the accessibility of materials that could be used for constructing solar cells (Table 1) is likely to be increasing in many regions as the population living in large urban centres progressively grows. This is because the composition of waste streams in many urban centres is changing as an increasing proportion of the population have sufficient disposable income to buy consumer goods that were previously inaccessible. Additionally, many large urban centres are experiencing a large and growing “e-waste” problem as large amounts of obsolete electronic equipment from high-income countries are being dumped in many parts of the world (UNEP, 2006). Obsolete electronic equipment now represents about 8% of most municipal waste streams and this proportion is growing rapidly throughout the world (UNEP, 2006).

Natural products in urban areas that have the potential to be raw materials for solar cell construction (Table 1) include fruit, vegetables and other foodstuffs (particularly for dyes); local vegetation (dyes); mangrove mud (a source of sulphides and sulphur); beach sand (generally contains the titanium-bearing minerals ilmenite and rutile for making titanium dioxide); and seaweed (a source of iodine).

Table 1

Some potential raw materials for solar cell construction from natural products and waste streams and their possible uses

Material	Products and uses
Galvanised iron fittings (screws, nails, washers etc.); discarded household batteries	Source of zinc for the semiconductors ZnO & ZnS
Copper wire from discarded electrical and electronic equipment	Making electrical connections; source of copper for the semiconductors Cu <sub>2</sub> O, CuO & Cu <sub>2</sub> S; soluble Cu salts for aqueous electrolytes
NiCad rechargeable batteries	Source of cadmium and nickel for the semiconductors CdS, CdO, NiO
Soldered connections from discarded electronic equipment; steel cans	Source of tin for the semiconductors SnO <sub>2</sub> , SnS and SnS <sub>2</sub> ; source of lead for PbS (for solder that contains 40% Pb)
Scrap iron	Source of the semiconductors Fe <sub>2</sub> O <sub>3</sub> , FeS <sub>2</sub> ; soluble Fe salts for aqueous electrolytes
Broken light bulbs	Tungsten filaments can be used to make the semiconductors WO <sub>3</sub> and WS <sub>2</sub>
Scrap aluminium foil	Electron donor for electroplating solar cell electrodes and the chemical reduction of chemicals used in solar cell construction
Soot and pencil “leads”	Carbon for counter electrodes in photoelectrochemical cells
Fruit, vegetables and local vegetation	Natural dyes for sensitizing large band-gap semiconductors
Mud in mangrove areas and coastal salt marshes	Source of sulphur for making sulphide semiconductors
Seaweed	Source of iodine

### 3. Methods and materials

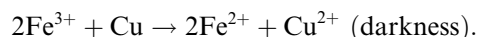
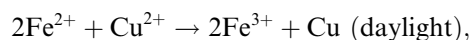
#### 3.1. Preliminary work

Preliminary testing indicated that photoelectrochemical cells using dye-sensitized large band-gap oxide semiconductors (O'Reagan and Grätzel, 1991; Grätzel, 1999, 2001) produced the best results under the constraints imposed by this study, and this type of cell became the focus of much of the work that was carried out. However, it was not possible to construct the standard Grätzel – type cell because of the difficulty in obtaining materials to make the  $I_2/I_3^-$  electrolyte typically used for charge transfer within this type of photoelectrochemical cell.

Although an iodine/iodide solution can be found in pharmacies in some countries (sold as “tincture of iodine”), it is not readily available in many parts of the world. It is also expensive to buy and is progressively being replaced in antiseptics by the organic-iodine compound povidone which is much less effective for charge transfer and is even more expensive (per unit mass of  $I_2$ ) than iodine/iodide formulations. Testing indicated that it was possible to extract sufficient iodine from seaweed to make solar cells, but it was prohibitively difficult to do so because of the large amount of dried seaweed and the labour that was needed to produce a few milligrams of iodine. Additionally, it is unlikely that large amounts of seaweed would be available in regions with drinking water quality and sanitation prob-

lems because of the extent that coastlines in these regions have been degraded by high population densities and pollution.

Of the alternatives to  $I_2/I_3^-$  tested, the most readily accessible, and the cheapest to buy or the easiest to make from recycled materials was an iron–copper redox system (Licht, 2002) that uses the following reactions for charge transfer:



This redox couple provides an energy storage system that can enable solar cells to function rather like rechargeable batteries with an inbuilt solar charging unit (i.e., as photoelectrochemical storage cells – Licht, 2002). It does, however, complicate cell construction because separate half-cells are required for the iron and copper components of the redox couple.

Testing indicated that the simplest way of constructing two connected half-cells without access to semi-permeable membranes or without using separate vessels with a connecting salt bridge was to construct the half-cells in separate arms of a clear plastic “U-tube” with a tissue paper or cotton–wool plug in the base of the tube. The most readily available source of plastic tubing in domestic waste streams was found to be flexible plastic drinking straws which had a high level of transparency but which were also generally brightly coloured. Translucent white-coloured straws with coloured stripes were also found to be suitable containers for solar cells, but the power output from constructed cells was generally only about 70% of that produced by straws with a greater degree of transparency. In this study, 10 mm diameter clear vinyl tubing salvaged from a domestic waste stream was also used as construction material.

Another likely constraint for making dye-sensitized solar cells under field conditions is the difficulty in obtaining TiO<sub>2</sub> in many regions, and this materials can not be easily made or extracted from waste materials (despite the fact that titanium dioxide is a common constituent of house paints and white-coloured plastics). By contrast, testing in this study indicated that zinc could easily be removed from widely available zinc-plated metallic objects (screws, nuts, bolts, nails, washers etc.) using household cloudy ammonia, and that this solution could be used to make ZnO coatings that could be used as a replacement for TiO<sub>2</sub> on dye-sensitized electrodes.

#### 3.2. Sources of materials and cell construction methods

The materials shown in Table 2 were used to construct the solar cell.

Flexible plastic straws were folded at the corrugated hinge and then trimmed with scissors to form a “U-tube” with each arm consisting of a piece of straw with a length of about 2.5 cm. The two arms were then bound together with a piece of wire or cotton thread (Fig. 1). A small plug of tissue paper was pushed to the bottom of one arm of the U-tube and covered with a 5 mm layer of dry ferrous

Table 2  
Materials used to construct the solar cell

Material	Source(s)
Pieces of 0.2–0.5 cm diameter multi-strand copper wire	Wire was salvaged from electrical and computer equipment disposed of during local government “white goods” disposal events
Tinned multi-strand copper wire	Wire was salvaged from electrical and computer equipment disposed of during local government “white goods” disposal events
Zinc solution for the deposition of ZnO	Zinc-plated screws, wire, bolts, washers and nuts were obtained from the gutters of busy roads, from construction sites and the non-putrescible component of domestic waste streams. Zinc was dissolved from these items by soaking them in a solution of household cloudy ammonia
Copper (cupric) sulphate crystals	Purchased from a hardware store. Also was made by reacting scraps of copper wire with sulphuric (“car battery”) acid and evaporating the solution to precipitate cupric sulphate crystals
Sulphuric acid	Salvaged from a car battery
Iron (ferrous) sulphate crystals	Purchased from a hardware store. Also was made by reacting iron filings and steel wool with sulphuric acid and evaporating the solution to precipitate ferrous sulphate crystals
Cloudy ammonia (solution of ammonium hydroxide and ammonium chloride)	Laundry supply section of a supermarket
Aluminium foil as an electron source for electroplating zinc	Foil wrapping and aluminium cans in the non-putrescible component of domestic wastes
Transparent plastic tubing	Plastic drinking straws and clear vinyl tubing in the non-putrescible component of domestic wastes

sulphate crystals which were introduced using a small scoop made from a piece of plastic straw. The same amount of copper sulphate crystals were then scooped into the second arm of the U-tube.

A 2 cm length of plastic coating was stripped from one end of two or more pieces of multi-strand copper wire, and a smaller amount of plastic was removed from the other end of the wires for electrical connection. The longer section of bare wire was then inserted into side of the U-tube that contained the copper sulphate crystals.

The plastic coating was stripped from tinned multi-strand copper wire in a similar way. The longer section of bare wire was then put into a small plastic container containing cloudy ammonia and a few zinc-plated metal items (such as nuts, bolts, washers etc.). The wire ends were submerged in the cloudy ammonia solution and a small piece of aluminium foil was added to the solution. After about 2 min, the wire was removed from the solution, washed with clean water and dried with a piece of tissue paper. The plated wire strands were then left in the sun for about 30 min to allow the metallic zinc film and part of the underlying tin film to oxidise to form a mixed ZnO–SnO<sub>2</sub> coating on the wire.

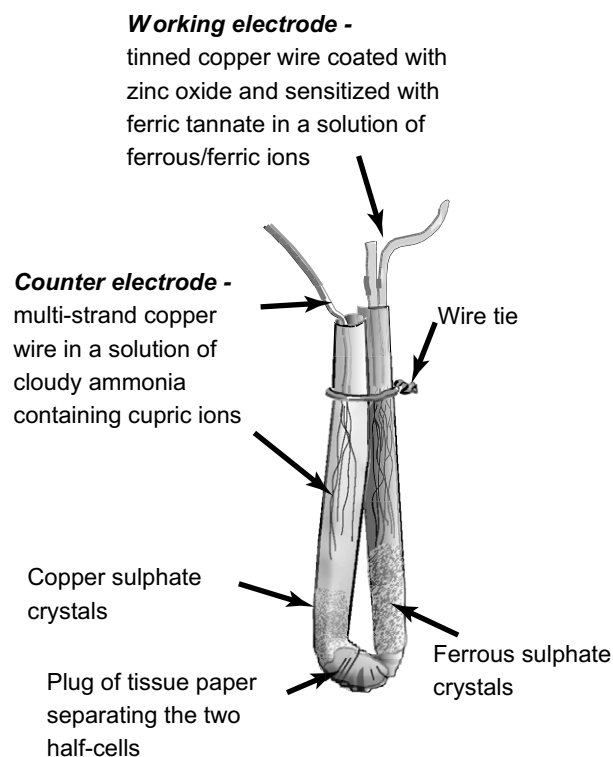


Fig. 1. Schematic view of the photoelectrochemical cell indicating key features of its construction in a plastic drinking straw. Similar construction methods apply to cells constructed in larger diameter clear plastic tubing.

A number of natural plant dyes were tested for their effectiveness of sensitizing the zinc oxide coating on the working electrode. These included chlorophyll extracted from soft-leaved herbs by pounding and water leaching; anthocyanins extracted from pomegranates and red rose petals with water; carotenoids extracted from grated carrots with denatured alcohol; and curcumin extracted from turmeric with denatured alcohol.

However, of the dyes tested, ferric tannate was found to be the most effective sensitizing agent. This was made by adding a teaspoon of fresh tea leaves to a small plastic container containing about 20 mL of cold water. About a quarter of a teaspoon of dry ferrous sulphate was then added to the container and the solution stirred. The solution slowly changed to a faint violet colour due to the presence of water-soluble ferrous tannate, and then became an intense blue-black colour as a suspension of insoluble ferric tannate progressively formed. Zinc and tin oxide films on wire were immersed in freshly made solutions of ferrous tannate (before significant oxidation to ferric tannate had taken place) and were put in the sun to dry for about 30 min to allow ferric tannate to form on the wire strands.

After drying, the dye-treated wire was inserted into the arm of the U-tube containing the ferrous sulphate crystals. Household cloudy ammonia was used to fill the arm of the U-tube containing the copper sulphate crystals, and water was used to fill the other arm of the tube.

Construction of cells in the 10 mm diameter clear vinyl tubing was carried out in much the same way, except that 0.5 diameter tin solder wire was used to construct the working electrode rather than tinned copper wire.

### 3.3. Construction and use of an electrolysis cell

An electrolysis cell for generating chlorine with the constructed solar cells was made by inserting graphite (pencil “lead”) electrodes through the screw-cap of a small plastic bottle into which 100 mL of a 1% salt solution was placed. The salt solution was made by adding one level teaspoon of table salt to 1 L (four cups) of water. The plastic bottle was placed in a water bath in a covered polyurethane foam container to keep it cool to reduce the loss of chlorine from volatilization and the formation of chlorate ions. Chlorine concentrations in the electrolysis cell were measured using an *o*-tolidine test kit.

## 4. Results and discussion

The open-circuit voltage of constructed photoelectrochemical cells in full sunlight was about 0.4–0.6 V, and the short-circuit current produced by the cells was typically 1–2.5 mA cm<sup>-2</sup>. Testing of cells outdoors with varying resistive loads under approximately full-sun conditions indicated that they had an efficiency of about 0.5% with fill factors of about 0.3–0.7. The dark current of the cells was about 0.02 mA cm<sup>-2</sup>, indicating that there is a significant galvanic component to their power output. This suggests that the cells will be susceptible to corrosion and are only likely to have a short life, although cells constructed in this study have continued to function for at least a month after construction.

A short life-span may not be a significant issue under conditions when raw materials are readily available, as individual cells can be constructed within 10 min at little or no cost. The much more significant issue is the size constraint that is imposed by the nature of raw materials salvaged from waste streams and the construction methods that need to be used under field conditions. As individual cells constructed in drinking straws only produce about 3 mA of current in full sun, very large numbers of cells need to be assembled into an array to produce a significant amount of electrical power. The amount of labour and time required to build an effective solar array is much smaller when larger diameter tubing is available, as individual cells can produce many times the current than is possible in small devices constructed in plastic drinking straws.

For this reason, an array to test the feasibility of producing chlorine for water disinfection was constructed with 10 mm diameter vinyl tubing rather than with drinking straws. The array had a voltage of 5 V and produced 200 mA of current in full sun. This array produced chlorine at a rate of 4 mg h<sup>-1</sup> (Fig. 2), or enough chlorine to disinfect about 1–2 L of drinking water each hour.

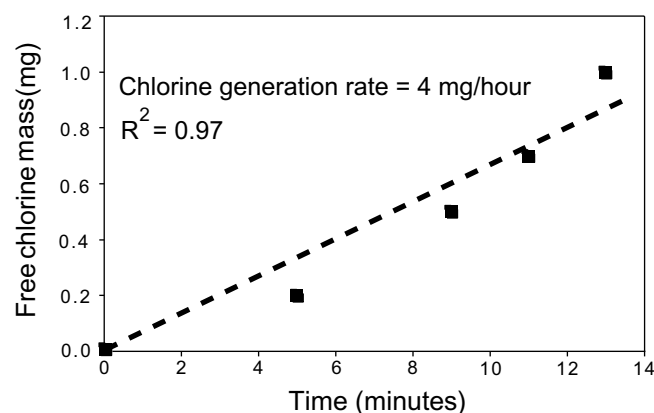


Fig. 2. Rate of chlorine production by the electrolysis of a 1% salt solution from a solar cell array with a voltage of 5 V and a current of 200 mA in full sun.

## 5. Conclusions

This study has demonstrated that it is possible to construct effective solar cells for generating small amounts of electricity for drinking water chlorination without specialised laboratory equipment and using materials salvaged from waste streams and readily available chemicals. Although a considerable amount of additional work would be required to demonstrate that this is a practicable approach for dealing with waterborne health and sanitation problems, the results are sufficiently encouraging to suggest that further research in this area is warranted.

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