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Water recycling with PV-powered UV-LED disinfection

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Abstract

Water is in short supply with countries vying for access to river heads. Hong Kong (HK) is no different. It relies on supply from Mainland China with other cities rivalling access. Yet there is still no great impetus for water conservation. This paper reports on progress in setting up a pilot biological wastewater treatment plant and a PV-powered UV-LED disinfection system plus a feasibility study carried out in conjunction with a local developer investigating the application of the treated water for irrigation. The objective is to incorporate the systems within a small-scale community for its contribution to water and energy conservation as well as establish the parameters for replication in other countries with potential up-scaling for urban application.

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1. Introduction

United Nations has designated 2005–2015 as the International Decade for Action highlighting Water for Life. Szollosi-Nagy, in a 2004 UN-sponsored seminar [1], identified that water can be the catalyst for peace, at the same time calling on the Active Management of Shared Water Resources to avoid conflict over the vital commodity. Disputes are common in central Kenya, where media report that rows over water have recently led to 16 deaths [2]. In SE Asia, the countries sharing the waters of the Mekong are in dispute over dams proposed upstream that threaten the water source of Laos, Cambodia

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and Vietnam downstream. Even when advantageous trade deals are agreed, growing demands create new pressures. The Hong Kong (HK) Special Administrative Region has for many decades sourced its water from the riverhead of the Dongjiang River in Mainland China, but now, newly developed cities in the region rival for closest access to the riverhead. While HK draws its water from across the border and its citizens complain of high cost and low quality, very little is being done to encourage water conservation in the home territory. Moreover, the responsibility is disparate with water supply quality being covered by one department and sewage systems by another. As with other services, there is a tendency to consider only centralised systems though these have long lead-in time, tending to be inflexible to change and extremely expensive large-scale infrastructure projects. Presently in HK, with a population of 6.28 million, 1.4 million cubic metres of sewage is produced every day. According to HK Environmental Protection Department (EPD) officers, 99% of that sewage is water. [3]

The impetus to promote biological wastewater treatment arose not only from concern for water conservation, but also the treatment process’s potential for generating methane gas as a secondary energy source, plus considering the advantages of de-centralised sewage treatment and its possible integration within new (residential) developments in a holistic approach to providing sustainable services. In remote areas of cultural and nature tourism, reclaimed water can be used for man-made wetlands and landscape irrigation.

2. Pilot project development

The University of Hong Kong's (HKU) Marine Campus is sited at Cape D’Aguilar, on the south side of HK Island. It operates a non-mains sewage system. Chu, in her thesis research, organised the addition of planted filtration beds extra to the sedimentation tank to form a small biological wastewater treatment process. As a botany project, Chu’s results highlighted the improved performance of plants fed with fertiliser, the organic residue of the biological wastewater system. [4] In 2002, the waters surrounding Cape D’Aguilar were designated a marine reserve and required the discharge from the system to be upgraded. Despite its known toxicity for organic life, a chlorination process was adopted to meet the raised standards required by HK’s EPD.

However, researchers at the Kadoorie Farm and Botanical Gardens (KFBG), a research facility affiliated to HKU, had co-operated with Chu, and later adopted biological treatment for its pig-farm waste, further extending the plant research to establish the performance of more varieties in the HK sub-tropical climate. (Fig. 1)

This second HKU research project revives the original Marine Campus biological treatment process adding large plastic tanks which culture algae and aquatic plants *Cyperus alternifolius* L., *Vetiveria zizanioides*, and *Canna generalis*, as suggested from the KFBG experience, to feed on the suspended solids and nutrients in the sewage. There is a degree of trial and error expected to establish optimum culture in this seashore location due to its varying salinity through the seasons. The quality of the sewage and effluent will be monitored regularly according to standards and criteria set by HK’s EPD (1991) [5] in order to identify this best configuration. The project seeks to meet WHO standards for irrigation-quality water. Until the standards have been documented and authorised by HK’s EPD, the discharge is required to be returned to the chlorination process before final discharge into the marine reserve (Fig. 2).
The impact of the 2003 Severe Acute Respiratory Syndrome (SARS) epidemic in HK and the region ensures continuing attention and concern for bacteria and viral spread. Presently, the relevant authorities require retention of final chlorine disinfection so that the biological treatment with UV disinfection is applied to a diverted stream of effluent that is returned to the chlorine disinfection system before final discharge into the marine reserve.

Ensuring appropriate disinfection with new equipment, UV-LED lamps and photovoltaic (PV) power generation are therefore a very critical aspect of the research.

Fig. 1. Kadoorie Farm System, 2004.

Fig. 2. Biological wastewater treatment process.
Establishing their effectiveness and the detailed monitoring procedures appropriately is presently holding back progress on the original pilot project but will provide an excellent opportunity for comparing the material and labour costs of chlorination and UV disinfection.

2.1. Standards

The HK government is cautious and follows accepted practice and standards rather than pioneering new approaches. The standards for potable water quality as set by the World Health Organisation (WHO) have been adopted in HK. No standards have been set to date for irrigation water from treated wastewater systems, though the US Environmental Protection Agency’s, Guidelines for Water Reuse, September 2004, are referenced. [6] The experience of the US states listed include three (California, Florida and Hawaii) with warm climate as well as significant agricultural industries with major food export trade, and are therefore particularly relevant. Importantly, the Guidelines refer to checks for the safety of reclaimed water from pathogens and emerging pollutants of concern, EPOC, noting the California State requirements for newly set-up treatment plants to test for certain bacteria monthly in the first year, then quarterly in the second year; after 2 years, testing may be discontinued with the approval of the State’s Department of Health. Florida also requires monitoring but at a different frequency. California appears to lead in the draft regulations for annual monitoring of municipal wastewater to check incidence of pharmaceuticals, endocrine disrupting chemicals and other chemical indicators. The Guidelines also state that “although no illnesses to date have been directly connected to the use of reclaimed water, in order to better define pathogens and EPOCs contained in reclaimed water, it is recommended to continue with ongoing research and additional monitoring for Giardia, Cryptosporidium and other EPOCs” [6]. It should be highlighted that the standard of the reclaimed water will always be dependent on the quality of the original (municipal) water supply and that reclaimed water will have a higher concentration of the constituents of the original supply.

2.2. Disinfection

Chlorination is a common disinfection treatment for wastewater treatment, although it has considerable drawbacks in terms of transportation, handling and storage of hazardous and corrosive chemicals. Additionally, the chlorine-treated effluent is known to be toxic to aquatic organisms [7,8], a point particularly relevant to discharge into a marine reserve. The alternative, ultra-violet (UV) light radiation, is gaining increasing application as the cost of that process reduce—due to greater commercialisation, quality and competitiveness of the equipment—whereas the increasing requirement, arising from concern for damage to organic life, to supplement chlorination with de-chlorination treatment adds to the costs of that process. The Guidelines report case studies of the change to UV disinfection including cost savings. UV radiation works by destroying a cell’s ability to reproduce and, according to the Guidelines for water reuse, is effective at inactivating most viruses, spores and cysts. UV light is classified in the wavelengths 100–400 nm and is further divided into three subgroups UV-C, 100–280 nm; UV-B, 280–315 nm, and UV-A, 315–400 nm. Present UV disinfection uses low- or medium-pressure mercury lamps and according to data from a US-based UV-disinfection manufacturer/distributor “95% of the ultraviolet light
emitted is at the mercury resonance line of 254 nm” [9]. However from 2006, under proposed European Union (EU) rules, mercury as a hazardous substance will no longer be acceptable. A fast-developing option is likely to be the UV-light emitting diode (LED). The UV-LED has already been identified for medical applications and currency verification and is beginning to be produced in commercial volumes resulting in considerably lower prices. UV-LED lamps have the advantage of an extremely long life—conservatively 20,000 h, but up to 100,000 h claimed—and very low electricity draw. In addition to relative robustness (minimal sensitivity to vibration), their application in UV disinfection treatment is particularly appropriate especially when sites in remote, off-grid areas require power from solar energy. Since the LED is semi-conductor technology, it is perfectly suited; in fact, it is exactly the reverse process of PV technology. UV-LEDs presently manufactured are in the waveband range of 370–400 nm, ie UV-A light. [10] The schematic for the proposed pilot PV-powered UV-LED disinfection system is shown in the attached Fig. 3. It is worth highlighting from the Solar Water Disinfection Manual (WHO website) that UV-A light, in the range of 320–400 nm, “has a lethal effect on human pathogens present in water …. UV-A radiation interacts directly with the DNA, nucleic acids and enzymes of the living cells, changes the molecular structure and leads to cell death. UV radiation also reacts with oxygen dissolved in water and produces highly reactive forms of oxygen (oxygen free radicals and hydrogen peroxides). These reactive molecules also interfere with cell structures and kill the pathogens” [11].

The PV array is to be installed outside the water treatment facilities, powering the UV-LED disinfection lamps. The PV modules are tracked at their maximum power point to

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![Fig. 3. Diagram of PV and UV-LED disinfection systems.](image-url)
optimise the energy yield. To cater for varying weather conditions, the power from the PV array is stored into the battery bank. After regulation of the voltage and current to supply the LED lamps, the disinfection process begins with energy from the sun. The complete process is to be monitored and controlled with an artificial intelligence (AI) programme to ensure the resulting water discharge will be up to the standards.

3. Applications

3.1. HK fishing village

At the same time as we are investigating and monitoring the biological procedure and developing UV-LED disinfection, we are also liaising with a local developer for the small-scale application of the process. The wastewater treatment is one part of a broader strategy that will integrate an appropriate range of renewable energy technologies (RET) as a part of the set-up of an ecological village on a small HK island. A large portion of the island is owned by a local developer who proposes the rehabilitation of the existing fishing village as a part of the island’s promotion as an education and nature centre appealing to tourists as well as the local HK population. The village is intended to be a living community with shops, home/offices and small businesses related to but not completely dependent on developing a cultural tourist industry. Cost studies, summarised below, of the benefits of water reclamation from the generated effluent indicate substantial “avoided costs” of the monthly water and sewage tariffs sufficient to arouse management companies’ interest. Clearly, these benefits will vary according to local tariffs but offer a significant incentive (See the chart in Fig. 4 below).

3.2. Fish ponds, wetlands and cultural tourism in remote areas

In the river deltas of Southern China, fish ponds are a traditional method of fish farming. Recent expanded housing construction around the ponds together with the loss of traditional reed bed plantations that feed off the nutrients in the ponds impose health hazards in the build-up of E. coli bacteria in the water, and in the fishes too. Low-cost biological waste treatment plants as proposed by our research would provide an appropriate intermediate technology for these developments. HK, as well as many parts of China and SE Asia, is developing tourism in remote sites with vernacular buildings of historic interest as well as areas of natural beauty and ecological biodiversity. Setting up biological wastewater treatment plants with UV disinfection assist in preserving and enhancing the natural ecology by providing irrigation water. It avoids the toxicity, cost

| Effluent generated (m³) | Water reclaimed per day @ 95% (m³) | Water reclaimed per month (m³) | Monthly Water tariff @ HK$4.58/m³ | Monthly Sewage tariff @ HK$1.2/m³ | Monthly savings HK$ | Annual Savings HK$ |
|------------------------|-----------------------------------|-------------------------------|-----------------------------------|-----------------------------------|---------------------|-------------------|
| 386(m³)                | 366.7(m³)                         | 11,001(m³)                    | HK$50,384                         | HK$13,201                         | HK$63,585           | HK$763,020         |
|                        |                                   |                               | US$6,459                          | US$1,692                          |                      | US$97,823         |

Fig. 4. Chart of predicted volumes + financial savings from reclaimed water.
and labour intensity of chlorination/de-chlorination procedures and the health hazards of providing no treatment at all Fig. 5.

3.3. Urban applications

This project also has a broader intention; biological wastewater treatment can have relevance to the urban context. Through the pilot project at HKU Marine Campus and then up-scaling to the HK fishing village it is expected to illustrate that the biological process can be safely and effectively replicated to contemporary developments. However, with the SARS epidemic very recent in our experience, health considerations will be the priority. Only after extensive trials and government, as well as public, confidence established can broader applications be expected. Given that scenario, new residential developments in which a localised biological wastewater treatment system can be integrated within the landscaping component would be most appropriate. The present practice of high-rise construction and the restrictions on plot ratio result in considerable landscaped areas. Localised treatment has the advantage of reducing the overall area required for a centralised plant, whereas current proposals for an extended chlorination plant in HK will require an additional 12 ha land to be “reclaimed” from HK’s harbour.

4. Conclusion

UV-LED disinfection is in its infancy and may still require considerable research and development input before commercial systems are available though all forms of LED are advancing with astonishing speed. The shared semi-conductor technology of LED and PV makes them natural partners in treatment plants designated for remote, off-grid locations. The known advantages of UV disinfection, its lack of handling hazardous materials and lack of toxic effluent, when compared with chlorination, have been further supported by the financial advantages reported in systems operating in the US. On completion of the HK pilot plant in 12 months time, we expect to be able to estimate accurately the set-up, operational and maintenance costs of a small-scale biological wastewater treatment system.
with PV-generated UV-LED disinfection. An additional deliverable of this pilot project is the comparable cost of the operational costs of chlorination versus UV disinfection. Our estimate for the financial benefits of water conservation in a community context where water supply and sewage treatment tariffs are a part of the equation clearly indicates that reclaimed water can provide a substantial saving merely in the “avoided cost” of those monthly/annual tariffs. Essentially, biological wastewater treatment is a low-cost process with advantages in providing planting that can be landscaped as an attractive feature. In densely developed communities with all the added risks of easy global travel but also fast transfer of disease, it is evident that the rigour and regularity of water quality monitoring procedures will dispel concerns for health and safety. Overseas experience and local small-scale demonstrations will be a part of the confidence-building process.

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