Solar radiation (PAR, UV-A, UV-B) penetration in a shallow maturation pond operating in a tropical climate

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ABSTRACT
Solar radiation is considered the primary route for disinfection of pathogenic bacteria in maturation ponds. There is scarce information on depth profiling and attenuation of Photosynthetically Active Radiation (PAR), UV-A and UV-B in shallow maturation ponds operating in tropical climates. Data of solar irradiance of the three wavelengths, together with turbidity, have been acquired from different depths for over one year in a shallow maturation pond (45 cm of depth) operating in Brazil. UV-A and UV-B were still detected at 10 cm from the surface, but from 15 cm both waves were undetectable. PAR was still detected at 30 cm of depth. Attenuation of irradiation showed to be related to turbidity. Attenuation coefficients were calculated and a model including log₁₀ of turbidity is proposed for predicting irradiance attenuation.

KEYWORDS
Solar irradiance; Attenuation coefficients; Shallow maturation pond.

INTRODUCTION
Sunlight is an abundant, free and natural resource and considered a major disinfection mechanism in waste stabilisation ponds (WSP). It has long been recognised to have a detrimental effect on enteric bacteria in water bodies (Fujioka et al., 1981), where the bacterial die-off rate is considered proportional to sunlight intensity (Polprasert et al., 1983; Gersberg et al., 1987; Curtis et al., 1992a, 1994; Moeller and Calkins, 1980; Whitlam and Codd, 1986).

Photosynthetically Active Radiation (PAR) and UltraViolet (UV) are of particular interest in WSPs for pathogen inactivation (Bolton et al. 2010b; Bolton et al. 2010a; Curtis et al. 1994; Curtis, Mara, and Silva, 1992a; Curtis, Mara, and Silva, 1992b; Davies-Colley, Donnison, and Speed, 2000; Davies-Colley et al. 1999; Hartley and Weiss, 1970; Holzinger and Lütz, 2006; Maïga et al. 2009; Muela et al. 2002; Silverman et al. 2013; Sinton et al. 2002; Whitman et al. 2008). A simple characterisation is as follows:

- Visible light radiation or Photosynthetically Active Radiation (PAR: 400 – 700 nm) is what the human eye can see and detect. Every type of light that can be seen is considered visible light, whether it is emitted by stars or light bulbs.
- Ultraviolet radiation has as its natural source the sun. Generally known to the public due to its ability to tan and cause sun burns; it also produces harmful effects on bacteria if exposed.
Their wavelengths are: Ultraviolet-A (UV-A: 320 – 400 nm) and Ultraviolet-B (UV-B: 290 – 320 nm).

UV-B is the strongest disinfectant, but its radiation only accounts for about 0.2% of the amount of total solar irradiance that reaches the ground at noon. UV-A totals about 5% and visible light represents around 50% of the total solar irradiance at noon (Shilton, 2005).

Sunlight has proven to be an effective agent in wastewater disinfection for bacteria and viruses, while not producing or contributing for the formation of toxic by-products (Metcalf and Eddy, 2003). UV disinfection can also be done in a compact way with special UV lamps that reproduce the UV spectrum, but maintenance costs are higher compared with natural sunlight disinfection in ponds, due to energy consumption and lamp replacement. In developing countries, like those in Latin America, WSPs are the most widely used treatment system (Noyola et al., 2012), and disinfection is done by natural means. The intensity of UV radiation that the ponds receive is not controllable when compared with systems using UV lamps for disinfection, and as a consequence efficiency can vary with shading, turbidity, latitude, altitude and time of day and year (WHO, 2002).

In natural water bodies, Haag and Hoigne (1986) concluded that virtually all effective light is attenuated fully before 1.0 m in depth. Balogh, Németh and Vörös (2009) confirmed that UV-B radiation is only limited to the first few centimetres in turbid water bodies, while in clear and deep water bodies it can penetrate several metres. This means that the impact of UV-B depends not only on attenuation, but also on depth and mixing processes in water bodies (De Lange, 2000). Balogh, Németh and Vörös (2009) consider that different components control UV attenuation and PAR attenuation in the same lake, and this could be the case for WSPs.

In waste stabilisation ponds, Bolton et al. (2010b) researched the extinction of sunlight along the depth of a facultative pond (1.5 m), measuring PAR, UV-A and UV-B with submersed sensors. Sunlight penetration for UV-B reached 8 cm in depth and 99% of the irradiance was absorbed in the first 2.5 cm. UV-A reached a depth of 15 cm and PAR penetrated further (43 cm), but 99% of PAR light were absorbed in the first 8 cm (Bolton et al., 2010b; Kohn and Nelson, 2007). Sunlight attenuation (through absorption and scattering) is very strong in maturation ponds due to high turbidity associated with large algal concentrations, producing different light attenuation properties in different ponds (Curtis et al., 1994).

There is scarce information on depth profiling and attenuation of Photosynthetically Active Radiation (PAR), UV-A and UV-B in shallow maturation ponds operating in tropical climates. The objective of this research was to collect data of sunlight irradiance from the surface and different depths of a shallow maturation pond (45 cm) over one year of continuous monitoring. A physicochemical parameter associated with attenuation rates (turbidity) was also intensively sampled over the research period.

METHODS

Experimental apparatus
The treatment line is composed of the following units in series treating urban wastewater: a UASB (upflow anaerobic sludge blanket) reactor followed by two maturation ponds, the first pond without baffles and the second pond with baffles, and a coarse rock filter, designed to serve a population of 250 inhabitants, treating around 40 m³/d. The location of the treatment
system is in Belo Horizonte, Brazil, latitude 19°53’ S in Cfa or Cwa humid subtropical climate according to Köppen classification. The focus of this research is on the second pond, which has only 45 cm of height. In this pond, the bottom sludge was previously removed before the research. There are longitudinal baffles inside the pond, but these do not influence or interfere with the penetration of sunlight, and their importance is on the removal of pathogenic organisms, which is not directly covered here.

**Solar intensity/irradiance reaching the pond surface and different depths in the liquid column**

Two different sets of sensors were used. An onsite weather station, the Wireless Vantage Pro 2® by Davis Instruments®, (Figure 1-A), acquired the total solar irradiance reaching the surface. Total solar irradiance, expressed in W/m², was stored every 10 min on a datalogger. The wavelength range covered by the weather station is from 300 nm to 1100 nm (includes most of the UV spectrum and the whole of the PAR). The meteorological station was installed in accordance with the Brazilian legislation for weather monitoring and recommendations made by Davis Instruments®.

A set of UV-A, UV-B, and PAR sensors was placed at different depths (5 cm, 10 cm, 15 cm, 20 cm and 30 cm) in the liquid column of the pond to record the amount of radiation received (Figure 1-B). The three different sensors, UV-A (SKU 421/I 43814); UV-B (SKU 430/I 43815); and PAR (SKL 2623/I 43817), a data logger (datalogger 2) and levelling plate were acquired from Skye Instruments® to conduct irradiance measuring in the second pond. Each sensor detected a different wavelength range. Photosynthetically Active Radiation (PAR) sensor read irradiance from 400 to 700 nm, and Ultraviolet A (UV-A) and Ultraviolet B (UV-B) sensors detected irradiance between 315 to 400 nm and 280 to 315 nm, respectively.

**Figure 1.** (A) Meteorological weather station for monitoring Total Solar Irradiance; (B) Example of UV-A, UV-B and PAR sensor placement inside the pond.
The sensors were placed at different levels each week for continuous readings and measuring of UV-A, UV-B and PAR, as shown in Table 1 and Figure 1-B).

**Table 1.** Example of measuring programme for UV-A, UV-B, PAR and turbidity at different depths.

<table>
<thead>
<tr>
<th>Month</th>
<th>Measurement days</th>
<th>Time monitoring per day (hours)</th>
<th>Sampling interval (minutes)</th>
<th>Depth profiling – from water surface of pond (cm)</th>
<th>Parameters measured in the field</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st month</td>
<td>1st week</td>
<td></td>
<td></td>
<td>5-10*</td>
<td>UV-A, UV-B and PAR; Turbidity</td>
</tr>
<tr>
<td></td>
<td>2nd week</td>
<td></td>
<td></td>
<td>15-20*</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3rd week</td>
<td></td>
<td></td>
<td>30</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4th week</td>
<td>24</td>
<td>10</td>
<td>5-10*</td>
<td></td>
</tr>
<tr>
<td>2nd month</td>
<td>1st week</td>
<td></td>
<td></td>
<td>15-20*</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2nd week</td>
<td></td>
<td></td>
<td>30</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3rd week</td>
<td></td>
<td></td>
<td>5-10*</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4th week</td>
<td></td>
<td></td>
<td>15-20*</td>
<td></td>
</tr>
</tbody>
</table>

*depth placement changes every time for different weeks in order to obtain more points throughout the depth and produce a better profile

Over a period of one year, turbidity was measured every hour on given days of the week of every month, in order to assist in the characterisation of the optical conditions in the pond.

**Solar irradiance attenuation**

Light can be measured as irradiance (I) which represents the number of photons per unit area of time (m\(^2\).s\(^{-1}\)) or by the amount of energy per unit of time (W.m\(^{-2}\)). \(I_d(z)\), downward irradiance intensity at a given depth, attenuates with depth and can be described by Equation (1), following Beer-Lambert’s law (Curtis et al., 1994).

\[
I_d(z) = I_{d(0)}. e^{-K_a.z}
\]  

where,

- \(I_d(z)\) – downward irradiance at a depth \(z\) (m\(^2\).s\(^{-1}\)) or (W.m\(^{-2}\));
- \(I_{d(0)}\) – downward irradiance at the surface (m\(^2\).s\(^{-1}\)) or (W.m\(^{-2}\));
- \(K_a(z)\) – attenuation coefficient for downward irradiance (m\(^{-1}\));
- \(Z\) – Depth from surface or reference point (m).

Median \(K_a\) values for PAR, UV-A and UV-B were calculated based on the pairs of irradiance and depth, in which \(I_{d(z)}\) were the mean values of irradiance and \(Z\) the depths in which irradiance was measured. For the surface of the pond (Z=0 m), irradiance of the three wavelengths was estimated based on the ratios recommended by Shilton et al. (2005), presented in the Introduction, multiplied by the total solar irradiance arriving at the surface (\(I_{d(0)}\)). Several pairs of I-Z (10 cm, 20 cm and 30 cm) where used to estimate \(K_a\) through non-linear least squares method, and applying the Solver tool in Excel for finding the value of \(K_a\) that minimized the sum of the squared errors.

As suggested by Bolton *et al.*, (2010b), turbidity was also measured during the whole experiment. Turbidity was measured every hour for four hours on selected days, either in the morning or afternoon by using a column sampler to sample up until the depth of the irradiance sensors.
RESULTS AND DISCUSSION

Overall solar irradiance reaching the pond’s surface is presented in Figure 2 for the whole monitoring period (12/07/2014 – 30/11/2015), contemplating over 1 year and 4 months of continuous monitoring. Time is divided up in intervals of 10 minutes. The variability of total irradiance increases as the time of day approaches noon and then proceeds to decrease due to less solar intensity. Variability is greater around noon, highlighting the influence that different seasons and cloud cover have on the amount of irradiance reaching the ground when it is at its highest point in the sky. The highest mean value was 687.89 W/m$^2$ at 12:50:00. Overall, solar irradiance was detected from 05:30:00 until 19:40:00.

![Figure 2. Hourly profile of Total Solar Irradiance reaching the surface of the ponds over the monitoring period.](image)

Depth profiling of irradiance started in June 2014 and went up until November 2015 (one year and five months) of continuous sampling. Five depths were investigated over the course of the period (Table 1). As expected, the amount of solar irradiance arriving at different depths in the pond diminishes as depth increases (Figure 3). UV-A and UV-B can only be detected until 5 cm and 10 cm in depth, afterwards at 15 cm, 20 cm and 30 cm only PAR persists due to its longer wavelength characteristics. The plotted data (mean values) in Figure 3 is for the whole monitoring period, contemplating all four seasons, and summarised into one day.

At 5 cm in depth, Figure 3-A, UV-A virtually mimics PAR and both follow a steep slope until their maximum mean value at 12:10:00, then proceed to decrease sharply as well until attenuating completely at the end of the day. UV-B on the contrary produces a gentle slope until 12:10:00 and then proceeds to decrease until completely attenuating. Although the wavelengths are different in nature, they all behave in the same way, all decreasing and increasing in irradiance at the same time. As expected, the plotted data of each wavelength follow a bell-like shape, the same as total solar irradiance (Figure 2).

At 10 cm in depth, the bell-like shape is present for PAR irradiance (Figure 3-B) and not affected by pond optics. UV-A and UV-B present a distorted and irregular shape. This can be attributed to pond optics, which in Figure 3-B shows that the UV spectrum is very much attenuated and affected by them. UV-A presents two peak values at around 11:50:00 and 16:50:00 and UV-B follows this trend (Figure 3-B).
The UV spectrum is undetectable at 15 cm, where only PAR irradiance is sensed and presented in Figure 3-C. The bell-like shape is still present at depths of 15 cm, 20 cm and 30 cm, but is more distorted over time. Note that each wavelength is detected before the other at different depths, where 15 cm is detected earlier and extinguishes later when compared with the other two depths (20 cm and 30 cm). PAR irradiance detected at 30 cm presents a more flattened shape and less energised when compared to the other two waves, but still retaining its bell shape. This can be attributed to the pond optics, where PAR at 30 cm is very much attenuated and affected by light scattering and attenuating objects.

Figure 3. (A) UV-A, UV-B and PAR irradiance reaching 5 cm in depth in the shallow pond; (B) UV-A, UV-B and PAR irradiance reaching 10 cm in depth in the shallow pond; (C) PAR irradiance reaching 15 cm, 20 cm and 30 cm in the pond. Note that the Y-axis scales are different.

Figure 4 shows how $K_a$ values for UV-A, UV-B and PAR, and turbidity behave over time. The time period used was between 9:00 and 16:00, since multiple samplings of turbidity were down during this period.

Turbidity values in all three graphs in Figure 4 are the same. Turbidity seems to increase from 09:00 until 12:00, reaching a peak value of 83 NTU at 11:00, decreasing to its lowest value at 16:00. During sampling this trend was observed on a general basis, where during the morning turbidity would increase with increasing solar intensity (algal activity), then proceed to decrease in value when approaching the end of the afternoon. Attenuation rates ($K_a$) of UV-A, UV-B and PAR also follow this trend (Figure 4-A, B and C), increasing in the morning and decreasing in rate during the afternoon. This suggests that turbidity affects the attenuation rates of the three waves and explaining better the variation of PAR (Error! Reference source not found.-C).
Figure 4. (A) Turbidity versus KaUVA over time; (B) Turbidity versus KaUVB over time; and (C) Turbidity versus KaPAR over time.

Due to the vast amount of data collected for PAR at each depth, Equation (1), with its traditional structure was used (reproduced in Equation (3), with the calculated value of $K_a$. $K_a$ for PAR was calculated using the Solver tool in Excel, minimising the sum of the squared errors. Two other equations were investigated (Equations (4) and (5)), on the basis that turbidity (TUR) and the log base 10 of turbidity ($\log_{10}(TUR)$) influence the attenuation coefficient. All equations are for a timeline from 09:00 – 16:00.

Table 2 shows the estimated $K_a$ values for all three equations, as well as the resulting Coefficient of Determination of the three models. Figure 5 (A, B and C) shows the goodness-of-fit in terms of the plot of observed results vs calculated results.

\[ I = I_0 \cdot e^{-26.65Z} \]  \hspace{1cm} (3)

\[ I = I_0 \cdot e^{-0.3486 \cdot \text{TUR}.Z} \]  \hspace{1cm} (4)

\[ I = I_0 \cdot e^{-14.0586 \cdot \log_{10}(TUR).Z} \]  \hspace{1cm} (5)

where

- $I$ – irradiance at depth $z$ (m$^2$.s$^{-1}$) or (W.m$^{-2}$);
- $I_0$ – irradiance at the pond surface (m$^2$.s$^{-1}$) or (W.m$^{-2}$);
- TUR – turbidity (NTU);
- $Z$ – Depth from surface or reference point (m).
Table 2. Ka values, Coefficient of Determination and Ka units for Equations 3, 4 and 5.

<table>
<thead>
<tr>
<th>Equation</th>
<th>Ka</th>
<th>Coefficient of Determination</th>
<th>Ka unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>26.65</td>
<td>0.83</td>
<td>m(^{-1})</td>
</tr>
<tr>
<td>4</td>
<td>0.349</td>
<td>0.50</td>
<td>m(^{-1}).NTU(^{-1})</td>
</tr>
<tr>
<td>5</td>
<td>14.06</td>
<td>0.78</td>
<td>m(^{-1}).LOG10(NTU(^{-1}))</td>
</tr>
</tbody>
</table>

Figure 5. (A) Observed and Estimated Irradiance for Equation 3; (B) Observed and Estimated Irradiance for Equation 4 and; (C) Observed and Estimated Irradiance for Equation 5. All graphs show the 45\(^{o}\) line of theoretical perfect fitting.

Equation 3 proved to produce the best fit when analysing observed I versus estimated I (Figure 5-A), presenting a Coefficient of Determination of 0.83 (Table 2), indicating a good fit. Equations 4 and 5 presented Coefficients of Determination of 0.50 and 0.78, respectively, being the latter closer to the Coefficient of Determination for Equation 3 and suggesting that LOG(TUR) could be included in the model for irradiance attenuation. Figure 5-B corresponds to the plotted observed and estimated data from Equation 4, and it is clear that just using turbidity will not produce a good fit. By applying the logarithm of turbidity (Figure 5-C), as done by Bolton et al. (2010), the observed and estimated values follow a more linear trend, approaching that of Figure 5-A and resulting in a better Coefficient of Determination. In fact, as suggested by Bolton et al. (2010), turbidity could indeed be a good indicator of attenuation and also a simple parameter to measure in any pond system. Note that in Table 2 the attenuation coefficients are presented in different units and cannot be compared directly with each other. When planning to apply these equations for other pond systems, it should be noted that the pond is shallow and turbidity did not change substantially along the depth.
CONCLUSIONS
The following conclusions can be made after solar irradiance was monitored at the surface and various depths of a shallow maturation pond over an extensive period of time. Results from total solar irradiance indicate that it varied greatly due to cloud cover, seasons and atmospheric conditions. This could in fact affect the amount of solar irradiance arriving at different depths in the shallow maturation pond (height of 45 cm). Depth profiling of solar irradiance has shown that UV-A and UV-B penetrated in the pond up to 10 cm, not being detectable at 15 cm. This impacts disinfection in WSPs. Moreover, these two wavelengths were very much affected by pond optics when compared to the stronger PAR wave, losing their identity at 10 cm and producing a very irregular shape. PAR continued to penetrate until 30 cm. Turbidity showed to influence the attenuation coefficient $K_a$. The attenuation coefficient was calculated using three different models (without turbidity, with turbidity, with $\log_{10}$ of turbidity). Even though the fitting of the models without turbidity and with $\log_{10}$ of turbidity were good, care should be taken in applying them to other ponds, due to the specificities associated with the pond under study (shallow depth and no expressive variation of the turbidity with depth).

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