Efficiency of domestic wastewater solar disinfection in reactors with different colors

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Abstract: The aim of this study was to evaluate the efficiency of domestic wastewater solar disinfection for agriculture reuse in solar reactors with different colors: black, white and raw concrete. After passing through a septic tank, the wastewater was conducted to the reactors until the water depth reaches 10 cm and it was exposed to sunlight for three consecutive days. The disinfection efficiency was evaluated by the concentration of E. coli, chemical oxygen demand, effluent temperature, global radiation, UV radiation, pH and total suspended solids and the data was analyzed by regression analysis. The results show that the effluent in different reactors had distinct temperatures: the highest rates were observed in the black reactor and the smallest in the white, however these differences were slight (on average 2 ºC) and the statistical analysis did not show a significant difference (p ≤ 0.05) between the efficiency in the reactors. The collected data allowed the development of a mathematical model that represents the remaining population of fecal coliforms in wastewater after being exposed to a certain dose of solar radiation. In conclusion, the reactor color does not alter the disinfection efficiency and the most important process variables are the UV-A radiation and total suspended solids concentrations.

Key words: Solar reactor, SODIS, solar radiation, fecal coliforms.

1. INTRODUCTION

The strong growth of the world population has had the effect of increasing the demand for water for both the public supply and for food production. Also, improper use of water and the release of untreated waste have negatively affected their quality. In this context, the reuse of wastewater in agriculture as a tool for water resources management allow a reduction in the demand for improved water quality and reducing the pollution of water resources.

However, before the widespread use of these waters in agriculture should be considered the presence of microorganisms that are potentially harmful to human health, requiring, therefore, the adoption of disinfection measures to obtain appropriate quality standards. Nevertheless, most methods of disinfection are expensive, difficult to apply on small farms or in low-income communities without an infrastructure to build and maintain the system.

In order for developing countries and/or low-income communities to use wastewater in agriculture without health risks, it is necessary to adopt an effective disinfection system with a low installation cost, easy to use and with little maintenance.

A promising alternative to fill these features is the process of solar disinfection (SODIS), since solar radiation is a source of clean and renewable energy that does not generate toxic byproducts and is available to all, especially to developing countries that are located on a region of the planet where solar radiation is more available.

The first study that found the effect of light upon bacteria and other organisms date from 1877 (Downes and Blunt 1877). However, it was only in the late twentieth century, in Beirut, Lebanon, that the SODIS technology was studied and developed as an inexpensive solution for the disinfection of drinking water (Acra et al. 1984). The results obtained showed that it is possible to decrease in three logarithms (log) the concentration of E. coli with only 75 minutes of exposure to solar radiation and that the larger germicidal effects are observed in wave amplitude corresponding to the UV rays.
The inactivation of pathogens by solar disinfection occurs due to the synergism between the UV-A radiation and water temperature (Bitton 2011). Temperatures at or above 45 °C accelerates the solar disinfection process (Malato et al. 2009). The main mechanism of inactivation of microorganisms by UV radiation is caused by damage to the genetic material (DNA / RNA) (Hijnen et al. 2006).

Several variables, such as total suspended solids (TSS), biochemical oxygen demand (BOD), hardness, pH, temperature, seasonal variations of light incidence and type of microorganism can change the efficiency of UV disinfection (Joyce et al. 1996; Solarte et al. 1997; Kehoe et al. 2001).

However, the most important variable is the type of microorganism present in the effluent because the UV disinfection is very efficient in removing bacteria, viruses, but protozoa cysts and helminth eggs have natural defense mechanisms that make them resistant to UV radiation (Kehoe et al. 2004; Heaselgrave et al. 2006; Boyle et al. 2008; Heaselgrave and Kilvington 2011).

According Meierhofer and Landolt (2009) SODIS technology is already being used for the disinfection of drinking water for more than two million people in 33 countries and the results obtained in these countries show that it is possible to drastically reduce the occurrence of diarrhea cases. The same authors estimated that the cost-benefit ratio of adopting this system can reach 1:49, that is, for every dollar invested at SODIS (purchase or exchange of containers) you can save 49 dollars in the health sector.

In Brazil, Sánchez-Román et al. (2007) showed that the SODIS is also effective to disinfect domestic wastewater (DWW) to levels suitable for reuse in agriculture using a concrete reactor with a square format of 1.5 meters across and 0.4 meters deep in water depths up to 0.20 m of effluent.

We hypothesize that the color of the concrete reactor can change the temperature of the effluent and improve the efficiency of SODIS. Therefore, the aim of this work was to evaluate the efficiency of DWW disinfection in three reactors with different coated colors in a simple and inexpensive solar disinfection system to reuse it in agriculture.

2. MATERIAL AND METHODS

2.1 Solar treatment and disinfection system

The system of treatment and disinfection of DWW was built on the Campus of the Faculty of Agricultural Sciences – UNESP, Botucatu, SP, Brazil. The geographical coordinates are 22º 51’ 12” South and 48º 25’ 45” West, and an altitude of 763 meters above sea level. It consists of a septic tank and three solar disinfection reactors based on concrete (Figure 1). The reactors have the shape of an inverted truncated cone with identical dimensions with a larger radius, smaller radius and height of 1.00 meters, 0.25 meters and 0.30 meters, respectively. This structural form of the reactors was adopted to ensure that the walls of the reactor do not produce shadows on the surface of the effluent for the longest time possible.

The experiment was conducted in the period from 03/25/2013 to 04/25/2013 and to evaluate the relationship between the efficiency of solar disinfection and synergism between the temperature and radiation reflection, each reactor received a different type of color coating.

- Reactor 1: The first solar disinfection reactor did not receive any coating. In this reactor, the wastewater was treated in direct contact with the raw concrete structure of the reactor.
- Reactor 2: The second reactor received a coat of white waterproof plastic paint, aiming to increase solar rays reflection inside the reactor.
- Reactor 3: The last received a coat of plastic waterproof black paint in order to increase the heat retention within the reactor’s wall and thereby increasing the wastewater temperature being treated.
2.2 Operation of the disinfection system, collection and analysis of samples

The effluent was collected in the Campus Wastewater Treatment Plant, and after passing through the septic tank (residence time of approximately 15 hours), was disposed in the reactors until the water depth reaches 10 cm. Thereafter, it was exposed to sunlight for three consecutive days, procedure that was carried out for four times. To evaluate the behavior of the population of *E. coli*, in which one of the four repetitions, three samples were collected daily from each reactor according to the 1060B Standard Methods and preserved in accordance with the 1060C Standard Methods (APHA 2005).

Table 1 shows the evaluated variables, the denomination of the adopted methods and their references.

<table>
<thead>
<tr>
<th>Variable (a)</th>
<th>Method</th>
<th>Reference (b)</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>E. coli</em></td>
<td>Enzyme Substrate Coliform Test</td>
<td>SM 9223B</td>
</tr>
<tr>
<td>COD</td>
<td>Closed Reflux, Colorimetric Method</td>
<td>SM 5220D</td>
</tr>
<tr>
<td>TSS (b)</td>
<td>Total Suspended Solids Dried at 103-105°C</td>
<td>SM 2540D</td>
</tr>
<tr>
<td>pH</td>
<td>Electrometric Method</td>
<td>SM 4500B</td>
</tr>
</tbody>
</table>

(a) *E. coli* – *Escherichia coli* (MPN 100 mL⁻¹); COD – Chemical oxygen demand (mg L⁻¹); TSS – Total suspended solids (mg L⁻¹); pH – Potential hydrogen

(b) Membrane filter: Ø 47 mm, 0.45 μm, Millipore: HAWP04700

(c) SM – Standard Methods (APHA 2005)

Figure 1 shows the three reactors with their 10 cm respective water depth of effluent exposed to solar radiation. With this 10 cm of water depth, the volume of wastewater being treated was...
approximately 47 L in each reactor.

2.3 Determination of solar radiation, UV radiation and temperature

Table 2 describes the main characteristics of the sensors used for the determination of the global solar radiation and UV radiation.

<table>
<thead>
<tr>
<th>Radiation sensors</th>
<th>Type</th>
<th>Global</th>
<th>Ultraviolet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brand</td>
<td>Eppley</td>
<td>±6.97µV/Wm²</td>
<td>211µV/Wm²</td>
</tr>
<tr>
<td>Calibration factor</td>
<td>305-2800nm</td>
<td>290-400nm</td>
<td></td>
</tr>
<tr>
<td>Response time</td>
<td>2s</td>
<td>5ms</td>
<td></td>
</tr>
<tr>
<td>Linearity</td>
<td>±1%</td>
<td>&lt;1%</td>
<td></td>
</tr>
<tr>
<td>Cosine</td>
<td>±5%</td>
<td>&lt;±10%</td>
<td></td>
</tr>
<tr>
<td>Temperature response</td>
<td>±1% from -20 °C to 40 °C</td>
<td>&lt;±0.1 °K</td>
<td></td>
</tr>
</tbody>
</table>

The effluent temperature was measured using an Incoterm thermo-hygrometer (Model: 7666.02.0.00) with readings in the range of -50 ~ 70 °C.

2.4 Statistical analysis

The evaluation of the effectiveness in the reduction of *E. coli* in each solar reactor was determined by studying the variables: global radiation dose (MJ m⁻²), UV radiation dose (MJ m⁻²), fraction of UV radiation in the global radiation, temperature of the effluent (°C), COD (mg L⁻¹), TSS (mg L⁻¹) and pH.

Data were analyzed using regression analysis in the R statistical software (version 3.0.1). To evaluate the influence of colors on the efficiency of the SODIS reactors, the response variable used was the ratio of the initial population (No) and the remaining population (N) of *E. coli* following exposure to solar radiation (y = N / No). Thus, the values of the dependent variable will always be less than or equal to one and always greater than zero.

At first, the function used to analyze the data and adjust the models was a logistic function with two parameters (S-shape function) or sigmoid function. This function can be used in the analyses of survival and dose response studies of microorganisms exposed to UV radiation (Kowalski et al. 2000).

Subsequently, using linear models and adopting as the response variable, the log reduction in *E. coli* population (log reduction = log (No / N)) were adjusted and compared twelve mathematical models. The parameters used to compare the models were the AIC (Akaike Information Criterion) and BIC (Bayesian Information Criterion). These parameters can be used to compare models in the same way as the analysis of variance and the model with lowest values for these two parameters is what best explains the data set in study (Crawley, 2002).

3. RESULTS AND DISCUSSION

3.1 Characteristics of the domestic wastewater

Table 3 shows the patterns evaluated of the effluent used in the solar disinfection process. The typical concentrations for septic tank effluent in warm climate regions are described by Von Sperling and Chernicharo (2005). According to these authors, the concentrations for COD, TSS and
fecal coliform (FC), are 400-450 mg L\(^{-1}\), 100-150 mg L\(^{-1}\) and \(10^7\)-\(10^8\) FC 100 mL\(^{-1}\), respectively. The comparison of these data with the average values obtained in this work shows that the effluent used presented a lower than expected physicochemical characteristics.

**Table 3. Characteristics of the effluent from the septic tank**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Average</th>
<th>Maximum</th>
<th>Minimum</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>E. coli</strong> (MPN 100 mL(^{-1}))</td>
<td>(1.29\times 10^6)</td>
<td>(4.61\times 10^6)</td>
<td>(1.32\times 10^6)</td>
<td>(1.04\times 10^6)</td>
</tr>
<tr>
<td>COD (mg L(^{-1}))</td>
<td>654.96</td>
<td>850.00</td>
<td>468.00</td>
<td>113.24</td>
</tr>
<tr>
<td>TSS (mg L(^{-1}))</td>
<td>180.33</td>
<td>219.00</td>
<td>146.00</td>
<td>20.33</td>
</tr>
<tr>
<td>Temperature (ºC)</td>
<td>22.50</td>
<td>25.30</td>
<td>20.50</td>
<td>1.54</td>
</tr>
<tr>
<td>pH</td>
<td>6.17</td>
<td>6.71</td>
<td>5.93</td>
<td>0.19</td>
</tr>
</tbody>
</table>

The World Health Organization (WHO) recommends that *E. coli* population for unrestricted wastewater reuse in agriculture must be \(\leq 1000\) MPN 100 mL\(^{-1}\) (WHO 2006). In our experiment, only one of the four repetitions presented such level after the 3-day solar exposure. Therefore, for reusing in agriculture our effluent would need more exposure time for improving disinfection.

### 3.2 Variations in temperature

The results of Dunlop et al. (2011), who used plastic bags as reactors for SODIS, showed that the solar disinfection is most effective when the water temperature in the reactors is higher than 45 ºC. Moreover, according to Ubomba-Jaswa et al. (2010), when the water temperature exceeds 45 ºC, it is possible to completely inactivate the bacteria in water with high turbidity (NTU 100).

Therefore, considering that the effluent from septic tanks has a high concentration of FC and TSS, the purpose of this study was to use different coating colors in solar reactors in order to raise the temperature of the effluent (\(\geq 45\) ºC) during disinfection and therefore, increase the efficiency of the process.

The use of different colors provided differences in the temperatures of the reactors: in the black and white reactors the temperatures were, respectively, the highest and lowest. However, these differences were small, with a maximum difference of 3.5 ºC with a mean difference of 2 ºC. The maximum temperature of 36.2 ºC was obtained in the black reactor.

### 3.3 Statistical analysis

Figure 2 shows the remaining population of *E. coli* in relation to the dose of solar radiation in each of the three reactors studied.

First, a mathematical model for each reactor data set was adjusted (Eqs. 1, 2 and 3). The models are:

**White reactor model:**

\[
y = \frac{\exp(1.936 - 0.2321*D)}{1+\exp(1.936 - 0.2321*D)}
\]

**Concrete reactor model:**

\[
y = \frac{\exp(2.1111 - 0.2321*D)}{1+\exp(2.1111 - 0.2321*D)}
\]

**Black reactor model:**

\[
y = \frac{\exp(2.00396 - 0.2321*D)}{1+\exp(2.00396 - 0.2321*D)}
\]
Subsequently, we developed a general model (Eq. 4) with all the data obtained in the three reactors, as follows:

**General model:**

\[
y = \frac{\exp(2.017 - 0.2321*D)}{1+\exp(2.017 - 0.2321*D)}
\]  

(4)

where:

- \( y \) – remaining fraction of *E. coli* population in the DWW
- \( D \) – solar radiation dose (MJ m\(^{-2}\))

*Figure 2. Remaining *E. coli* population in relation to the dose of solar radiation in the three reactors.*

The comparison between the four models shows a marked similarity between them, although the main difference is related to the respective intercepts (Figure 3).

*Figure 3. Comparison between the four sigmoid models adjusted.*
The analysis of variance showed no statistically significant difference at 5% probability among the four models (p = 0.6723). This finding indicates that different colorations of the reactors did not influence the efficiency of the process. Therefore, the collected data can be analyzed together without considering the effect of colors on the efficiency of the SODIS. For this reason, data from the three reactors were grouped and analyzed using a simple linear function and adopted as the response variable log reduction in the E. coli population (log (No/N)).

Figure 4 shows the logarithmic reduction of E. coli population in relation to the dose of solar radiation.

With these data, twelve linear mathematical models were adjusted with the logarithmic reduction in E. coli population as the response variable, which are described in Table 4.

Table 4. Adjusted linear models and their respective values of AIC and BIC.

<table>
<thead>
<tr>
<th>ID</th>
<th>Model (a)</th>
<th>AIC (b)</th>
<th>BIC (c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>( L_R = 2.0488041 + 1.0311354<em>UVD - 0.0141384</em>D + 0.0422974<em>UVF - 0.0099408</em>T - 0.0048107<em>TSS - 0.0003507</em>COD + 0.1139057*pH )</td>
<td>125.87</td>
<td>153.26</td>
</tr>
<tr>
<td>B</td>
<td>( L_R = 1.3526724 + 0.9462034<em>UVD - 0.0128993</em>D + 0.0264169<em>UVF - 0.0077028</em>T - 0.0055201<em>TSS - 0.0002426</em>COD )</td>
<td>125.06</td>
<td>149.41</td>
</tr>
<tr>
<td>C</td>
<td>( L_R = 1.238351 + 1.019292<em>UVD - 0.014777</em>D + 0.027910<em>UVF - 0.009404</em>T - 0.005543*TSS )</td>
<td>123.68</td>
<td>144.98</td>
</tr>
<tr>
<td>D</td>
<td>( L_R = 1.2847796 + 0.8680155<em>UVD - 0.0099198</em>D + 0.0199524<em>UVF - 0.0057328</em>TSS - 0.0003471*COD )</td>
<td>124.26</td>
<td>145.57</td>
</tr>
<tr>
<td>E</td>
<td>( L_R = 1.080301 + 0.956276<em>UVD - 0.011848</em>D + 0.020055<em>UVF - 0.005843</em>TSS )</td>
<td>123.65</td>
<td>141.91</td>
</tr>
<tr>
<td>F</td>
<td>( L_R = 0.347024 + 1.510681<em>UVD - 0.030318</em>D + 0.049441<em>UVF - 0.014080</em>T )</td>
<td>138.86</td>
<td>157.12</td>
</tr>
<tr>
<td>G</td>
<td>( L_R = 1.184974 + 1.067930<em>UVD - 0.016463</em>D - 0.006128*TSS )</td>
<td>122.69</td>
<td>137.91</td>
</tr>
<tr>
<td>H</td>
<td>( L_R = 1.2315 + 0.034786<em>UVF + 0.030147</em>D - 0.006822*TSS )</td>
<td>128.10</td>
<td>143.31</td>
</tr>
<tr>
<td>I</td>
<td>( L_R = 1.46359 + 0.030694<em>D - 0.007579</em>TSS )</td>
<td>129.37</td>
<td>141.54</td>
</tr>
<tr>
<td>J</td>
<td>( L_R = 1.254741 + 0.703179<em>UVD - 0.006492</em>TSS )</td>
<td>121.75</td>
<td>133.92</td>
</tr>
<tr>
<td>K</td>
<td>( L_R = 0.198141 + 0.041939*D )</td>
<td>162.80</td>
<td>171.93</td>
</tr>
<tr>
<td>L</td>
<td>( L_R = 0.15802 + 0.97131*UVD )</td>
<td>145.81</td>
<td>154.94</td>
</tr>
</tbody>
</table>

(a) \( L_R \) – Logarithmic reduction in E. coli population; \( D \) – Solar radiation dose (MJ m\(^{-2}\)) ; \( UVD \) – UV radiation dose (MJ m\(^{-2}\)); \( UVF \) – UV fraction (%); \( T \) – Temperature (ºC); \( TSS \) – Total suspended solids (mg L\(^{-1}\)), \( COD \) – Chemical oxygen demand (mg L\(^{-1}\)), \( pH \) – Potential hydrogen

(b) AIC – Akaike Information Criterion

(c) BIC – Bayesian Information Criterion
The evaluation of the AIC and BIC parameters in Table 4 shows that the lowest values are associated with the J model, which is therefore the best fit. The significant variables of this model are the UVD and TSS.

Table 5 describes the estimated values for the parameters of model J and their values for the t-test. The $R^2$ value obtained for this model was equal to 0.8277.

Table 5. Descriptive statistics of the adjusted linear model.

|          | Estimate | Standard error | t value | Pr(>|t|) |
|----------|----------|----------------|---------|----------|
| Intercept| 1.254741 | 0.212898       | 5.894   | 2.5e-08 *** |
| UVD      | 0.703179 | 0.053311       | 13.190  | < 2e-16 *** |
| TSS      | -0.006492| 0.001231       | -5.275  | 4.49e-07 *** |

(a) Significant code: ‘***’ 0.001; ‘**’ 0.01; ‘*’ 0.05; ‘.’ 0.1; ‘ ’ 1

Considering that the model J has been adjusted with the log reduction in the $E. coli$ population as the response variable, the model can be rewritten according to the following Eq. 5:

$$ y = \frac{N}{N_0} = \frac{1}{10^{(1.254741 + 0.703179*UVD – 0.006492*TSS)}} $$  

where:

- $N$ – remnant population of $E. coli$ in the DWW (MPN 100 mL$^{-1}$)
- $N_0$ – initial $E. coli$ population in the DWW (MPN 100 mL$^{-1}$)
- UVD – cumulative dose of solar UV radiation (MJ m$^{-2}$)
- TSS – concentration of the total suspended solids (mg L$^{-1}$)

In Figure 5, the graph of Eq. 5 is shown for the different concentrations of suspended solids (50, 100, 125, 150, 175 and 200 mg L$^{-1}$). It is observed that for the same doses of UV radiation, the SODIS efficiency is inversely proportional to the concentration of TSS.

![Graph showing the relationship between UV radiation dose and remaining E. coli population for different TSS concentrations](image)

Figure 5. Remaining population of $E. coli$ after domestic wastewater was exposed to the UV component of solar radiation for different concentrations of TSS, according to Eq. 5.

The amount of solar energy necessary to disinfect DWW is a value that should be established as a solar radiation dose, which depends mainly on the season of the year and the latitude (Sánchez-
Román et al. 2007). For example, considering a DWW with 50 mg L⁻¹ of TSS, an initial *E. coli* population of $1.29 \times 10^6$ MPN 100 mL⁻¹ (mean value showed in Table 3) and a desired final population of *E. coli* equal to 1000 MPN 100 mL⁻¹, according to Eq. 5 the total UV radiation dose required will be at least 3.1 MJ m⁻². However, if the TSS concentration increases to 200 mg L⁻¹, the total energy necessary will be at least 4.9 MJ m⁻².

Therefore, if the necessary solar radiation dose and the incident solar radiation in certain location are known, it is possible to determine the required time of solar exposure for DWW disinfection. Exemplifying, the Table 6 shows the incident solar and UV radiation in two different days in three locations of the world. The global solar radiation was calculated by Allen et al. (1998) methodology and the UV radiation was estimated in 5% of the solar radiation.

**Table 6. Incident solar and UV radiation in two different days of analysis in three locations of the world.**

<table>
<thead>
<tr>
<th>Location</th>
<th>Latitude</th>
<th>Date of analysis</th>
<th>Solar radiation (MJ m⁻² day⁻¹)</th>
<th>UV radiation (MJ m⁻² day⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antofagasta, Chile</td>
<td>23° 38’ 30” S</td>
<td>February 15</td>
<td>20.6</td>
<td>1.03</td>
</tr>
<tr>
<td></td>
<td></td>
<td>August 15</td>
<td>15.6</td>
<td>0.78</td>
</tr>
<tr>
<td>Mogadishu, Somalia</td>
<td>1° 48’ 2” N</td>
<td>February 15</td>
<td>19.1</td>
<td>0.95</td>
</tr>
<tr>
<td></td>
<td></td>
<td>August 15</td>
<td>20.6</td>
<td>1.03</td>
</tr>
<tr>
<td>Bombay, India</td>
<td>18° 58’ 45” N</td>
<td>February 15</td>
<td>16.0</td>
<td>0.80</td>
</tr>
<tr>
<td></td>
<td></td>
<td>August 15</td>
<td>21.8</td>
<td>1.09</td>
</tr>
</tbody>
</table>

Then, since for disinfecting a DWW with 200 mg L⁻¹ of TSS is necessary at least 4.9 MJ m⁻² of UV radiation it can be assumed, for instance, that around February 15 it will be required 4.76, 5.16 and 6.12 days of solar exposure, respectively, in Antofagasta, Mogadishu and Bombay. In the other hand, around August 15 it will be required 6.28, 4.76 and 4.49 days of exposure in Antofagasta, Mogadishu and Bombay, respectively. It is noteworthy that the solar radiation incidence in nearby days are very similar, consequently a single day can be used as a reference to determine the amount of time required for DWW solar disinfection.

A possible limitation of this study is the uncontrolled experimental condition, that is, variables such as the solar radiation, cloudiness and evaporation that are not controlled. However, the main objective of this work was to conduct the experiment under field conditions and to obtain practical results that would allow the adoption of SODIS technology in low-income rural communities for reusing of DWW in irrigated agriculture.

4. CONCLUSIONS

The results of this study show that the developed system was effective in the disinfection of the domestic wastewater and the use of different colors in the solar disinfection reactors did not affect the efficiency of the process. Besides, SODIS technology is able to disinfect DWW to levels suitable for agriculture reuse (*E. coli* population $\leq$1000 MPN 100 mL⁻¹) and the most important variables in the solar disinfection are the UV-A component of global radiation and total suspended solids concentration.

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