Treatment of food waste digestate using microalgae-based systems with low-intensity light-emitting diodes

Andrés Felipe Torres Franco, Scarlet da Encarnação Araújo, Fabiana Passos, Carlos Augusto de Lemos Chernicharo, César Rossas Mota Filho and Cleber Cunha Figueredo

ABSTRACT

Anaerobic digestion of food wastes coupled with digestate post-treatment using microalgae-based systems could recover large amounts of energy and nutrients worldwide. However, the development of full-scale implementations requires overcoming microalgae inhibition by high ammonia concentrations and low light transmittances affecting photosynthesis. This study evaluated the potential of microalgae-based reactors supplied with red light-emitting diodes (LEDs) at low intensity (660 nm and 15 μmol·m$^{-2}·$s$^{-1}$) to treat food waste digestate. LED reactors were compared with control reactors exposed to solar radiation. From a range of species in the inoculum, *Chlorella vulgaris* showed high adaptation to both lighting regimes and digestate environmental conditions, characterized by a C:N:P ratio of 74:74:1. Removal efficiencies for control and LED reactors were 84.0% and 95.8% for soluble chemical oxygen demand (COD) and 89.4% and 53.0% for ammonia, respectively. Approximately 50% of ammonia in control reactor and 15% in LED reactor was lost from the systems, whereas 17% and 36% of ammonia was transformed to organic nitrogen in control and LED reactors, respectively. Low-intensity LEDs maintained microalgae growth in levels similar to solar radiation and supported efficient digestate treatment, showing a potential for further application in optimization of full scale reactors at a relatively low energy cost.

Key words | *Chlorella vulgaris*, food waste digestate, light-emitting diodes, microalgae-based treatment

INTRODUCTION

Interest in anaerobic processes to treat food waste has grown intensely in the last decades due to its multiple advantages, including the possibility to recover energy. However, the liquid effluent from this process (i.e. digestate) usually contains high concentrations of organic matter, ammonia, phosphorus (Möller & Müller 2015) and, sometimes, pathogens (Sheets et al. 2015). Nutrients in food waste digestate could be recovered and applied in agriculture. However, direct application of digestate in agriculture is not recommended, as its carbon to nitrogen ratio could be not adequate for plant growth, which could also cause environmental impacts by e.g. ammonia volatilization.

Microalgae-based technologies, such as stabilization ponds, high-rate ponds and photobioreactors, have been applied as a promising alternative to recover nitrogen and phosphorus from food waste digestates (Mayers et al. 2017). However, there are many aspects of these processes that require further research and improvement. For instance, residual solids may limit light penetration, high levels of NH$_3$ in the digestate may cause inhibitory effects to microalgal growth and predators could significantly affect microalgal productivity (Triccoli et al. 2014; Sheets et al. 2015). Dilution has been used as a strategy to avoid ammonia inhibition and solids interference in light penetration, although it may not be a cost-effective alternative for full-scale implementation since it may demand high amounts of water, making that option unfeasible or unsustainable. High organic carbon and ammonia removals
have been achieved at relatively short hydraulic retention time (HRT) with the photo-activated sludge process, where consortia of microalgae and nitrifying bacteria removed ammonium efficiently (van der Steen et al. 2015). Photosynthesis in photobioreactors may ease oxygen limitations for bacterial growth, while artificial lighting can provide adequate photosynthetic active radiation (PAR) for microalgae growth. The use of light-emitting diodes (LEDs) as a light source for algal cultures has gained more attention in recent years since they can produce higher levels of radiation with relatively low energy demand, heating, carbon and area footprints (Mohammed et al. 2014), so their use may be a strategy to overcome shadowing effects of solids and optimize biomass production. Previous studies suggest that red light (particularly at 660 nm) at moderate to high light intensities (i.e. 50–2,000 μmol·m⁻²·s⁻¹) was optimal for microalgae growth in wastewaters and digestates (Zhao et al. 2015; Mohammed et al. 2014). However, those light intensities may still represent high energy consumption (0.54 kWh·kgCODremoved⁻¹) (COD = chemical oxygen demand) and even exceed photoinhibition levels reported for strains like *Chlorella vulgaris* under artificial lighting (Maxwell et al. 1995).

In order to enhance photobioreactors for microalgae-based treatment of concentrated digestates and wastewaters, LED lighting can be used to increase photic depth in hybrid ponds and tanks, reducing area requirements but still taking advantage of natural solar radiation, particularly in tropical climates. However, it is required to determine the minimum levels of PAR for microalgae photosynthesis and global treatment efficiencies. Thus, the current work intended to explore the potential of low intensity LEDs to support phototrophic activity in a microalgae-based system to treat food waste digestate under the hypothesis that a minimum level of 15 μmol·m⁻²·s⁻¹ can sustain photosynthesis and become a minimum value of reference for artificial lighting in further full-scale implementations.

**MATERIAL AND METHODS**

**Experimental set-up**

Laboratory-scale photobioreactors were operated in batch mode treating food waste digestate from an upflow anaerobic sludge blanket (UASB) reactor (Figure 1). The reactors consisted of six transparent acrylic tubes with a working volume of 800 mL, which were arranged vertically outdoors at the Engineering School of the Federal University of Minas Gerais (UFMG) (Belo Horizonte, Brazil – 19°52’11.04”S, 43°57’42.92”W). Mixing was achieved by motors operating at 6 rpm, installed at the top of each reactor and welded to a vertical shaft with mechanical paddles. Red LED lights in dimmable strips (wavelength 660 nm, ~25 W) were installed at the wall of the reactors (LED reactor), which were then covered with aluminium foil in order to supply a PAR of 15 μmol·m⁻²·s⁻¹. Control reactors were exposed to natural solar radiation with a daily mean PAR of 580 μmol·m⁻²·s⁻¹. Photoperiod for LED reactors was fixed for 12 hours, which was approximately the same time between dawn and sunset. Both LED and control reactors were built and operated in triplicate.

**Food waste digestate, microalgae and activated sludge inoculum**

Food waste digestate was obtained from a treatment system composed of an anaerobic completely stirred tank reactor, followed by a UASB reactor operated in series and fed with 500 kg of food waste per week obtained from the university canteens (UFMG, Belo Horizonte, Brazil).

Microalgae inoculum was obtained from a maturation pond treating municipal wastewater with high relative abundance of *Euglena* sp., *Scenedesmus* sp. and *C. vulgaris*. To increase the microalgae diversity in the initial inoculum, natural samples obtained from an urban reservoir in Belo Horizonte were concentrated with a phytoplankton net and added at a 1:1 ratio. For inoculation, 500 mL of the
microalgae previously collected was suspended with 2 L of food waste digestate and 2.5 L of distilled water to avoid ammonia toxicity, which resulted in total ammonia nitrogen (TAN) and total suspended solids (TSS) concentrations of 100 mg·L⁻¹ and 500 mg·L⁻¹, respectively. Each reactor was inoculated with 500 mL of this mixture. After an acclimation period of three days (Period I), TSS were measured and activated sludge from a municipal wastewater treatment plant (Belo Horizonte, Brazil) was added after 1 h settling at a ratio of 5:1 (microalgae:activated sludge). Working volume of each reactor was completed to 800 mL with a new pulse of food waste digestate and maintained in operation during 15 days (Period II).

COD, TAN and PO₄-P were determined on filtered samples every 48 h. Operational parameters including pH, dissolved oxygen (DO), temperature (T) and TSS were measured with the same frequency, and at 12 noon. Quantification of total Kjeldahl nitrogen (TKN), nitrate (NO₃-N), coliforms and Escherichia coli, as well as microalgae (by microscopy) was performed on the third day, immediately after the addition of activated sludge and digestate, and on the last day of the experiment. Flow cytometry analyses were performed for samples taken from inoculum and reactors at the end of the experimental period to establish the ratio of cells fluorescing to red light (670 long pass (LP) filter).

Experimental analyses

Food waste digestate was characterized by measuring total COD, soluble COD (S-COD), TAN, organic nitrogen (org-N), NO₃-N, soluble reactive phosphorus (PO₄-P), total phosphorus (total-P), pH, total alkalinity, TSS and volatile suspended solids (VSS) according to Standard Methods for the Examination of Water and Wastewater (Rice et al. 2012).

DO and temperature were measured directly in the reactors using a sensor (Hach® LDO101). pH was quantified using a benchtop pH-meter (Denver Instruments® UB-5). Concentrations of NO₃-N were measured by NitraVer® 5 Nitrate Reagent Powder Pillows (HM 8039). Total coliforms (TC) and E. coli were measured using the chromogenic substrate (Colilert-18/Quanti-Tray) technique. Microalgae populations were quantified by Utermöhl technique using an inverted microscope (Zeiss, Primovert, Germany). Chlorophyll-α (Chl-α) content was assessed by ethanol extraction and quantified by measuring absorbances at 645 and 663 nm with a spectrophotometer and using Becker’s equation. For flow cytometry, samples were fixed in paraformaldehyde and were evaluated using a FACSCanto™ II cytometer. Side scatter and the 488/530/30 laser and detectors were used. The fraction of cells fluorescence under red light was measured with a 670 LP Filter. Milli-Q water, saline solution and activated sludge were used as negative controls for flow cytometry.

Light intensity in the reactors was measured using a radiometer (Li-cor Li-189, USA). System’s performance was assessed in terms of chl-α productivity and COD, TAN and PO₄-P removal. chl-α productivity was estimated according to Equation (1) from chl-α triplicates obtained for the first and last days of the operational time [chl-α₀, considering A as the illuminated area (A = nDh) and t as the number of days of the operational period and Vᵢ and Vᵢ as initial and final volumes in each reactor.

\[
\text{chl-α productivity} = \frac{Vᵢ [\text{Chl-α}]₀ - Vᵢ [\text{Chl-α}]₁}{A \cdot t}
\]

Removal efficiencies were determined for S-COD, TAN and PO₄-P.

Statistical analysis

Statistical analysis included basic descriptive statistics and a repeated-measures analysis of variance (ANOVA) followed by a Bonferroni test performed in SPSS® for detecting significant differences between control and LED reactors treatment, (between-subject factors) and sampling time (within-subject factor) with a significance level of <0.05. F-values indicating differences are reported for the effects of time within reactor (F calculated for the effect of the interaction time-reactor) and between reactors (overall comparison). Normality was tested with a Shapiro–Wilk test. Data which did not follow normality were submitted to a log(1 + x) or a −1/lnX transformation in order to perform the ANOVA. Homoscedasticity was checked with Mauchly's test of sphericity and Greenhouse–Geisser degrees of freedom correction was used for autocorrelation when necessary.

RESULTS AND DISCUSSION

Food waste digestate characterization

Food waste digestate characterization is summarized in Table 1. The digestate presented high concentrations of organic matter, ammonia, phosphorus and solids. Relatively high pH and total alkalinity are common in food wastes, which are caused by ammonia bicarbonate buffers, CO₂
species concentrations of alkali compounds and bicarbonate and carbonate ions formed by successive dissociation reactions of carbonic acid produced during anaerobic digestion (Kang et al. 2017). Org-N was very low since the digestate was obtained from a food waste methanization reactor coupled to a UASB reactor and thus all org-N was previously ammonified.

Nutrient concentrations were high enough to support microalgal growth in control and LED reactors. Total alkalinity in food waste digestate presented high concentrations and secured inorganic carbon for autotrophic growth. An experimental C:N ratio based on S-COD of 1:1 and an N:P ratio of 73:1 suggests that carbon and phosphorus could have limited the total assimilation of TAN by autotrophic biomass, which was possibly affected since C:N ratio was relatively low when compared with optimum ratios reported for Chlorella sp. cultivated in wastewater with artificial light supply (C:N ratio of 5:1 to 10:1) (Yan et al. 2013) and optimum N:P ratio for reaching a maximum biomass production of Chlorella and nutrients removal (~10:1) (Choi & Lee 2015).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value (mean ± std dev.)</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total COD</td>
<td>1,856.7 ± 118.1</td>
<td>mg·L⁻¹</td>
</tr>
<tr>
<td>Filtered COD</td>
<td>808.3 ± 125.2</td>
<td>mg·L⁻¹</td>
</tr>
<tr>
<td>TAN</td>
<td>802.1 ± 20.3</td>
<td>mg·L⁻¹</td>
</tr>
<tr>
<td>TKN</td>
<td>805.1 ± 18.2</td>
<td>mg·L⁻¹</td>
</tr>
<tr>
<td>NO₃-N</td>
<td>12.5 ± 6.46</td>
<td>mg·L⁻¹</td>
</tr>
<tr>
<td>PO₄-P</td>
<td>4.9 ± 7.4</td>
<td>mg·L⁻¹</td>
</tr>
<tr>
<td>Total-P</td>
<td>10.9 ± 2.5</td>
<td>mg·L⁻¹</td>
</tr>
<tr>
<td>pH</td>
<td>7.82</td>
<td>N/A</td>
</tr>
<tr>
<td>Total alkalinity</td>
<td>4,116.8 ± 168.0</td>
<td>mgCaCO₃·L⁻¹</td>
</tr>
<tr>
<td>TSS</td>
<td>1,225 ± 125</td>
<td>mg·L⁻¹</td>
</tr>
<tr>
<td>VSS</td>
<td>1,045 ± 55</td>
<td>mg·L⁻¹</td>
</tr>
</tbody>
</table>

Microalgal productivity in control and LED reactors at the end of the operational period was 2.9 ± 2.1 and 31.3 ± 6.4 mg Chl-a·m⁻²·d⁻¹, respectively.

Chlorophyll increased in relation to C. vulgaris growth (Figure 3(b)), which was the only species present in both reactors from the beginning of the acclimation (Period 1)

**OPERATIONAL PARAMETERS**

Temperature, pH and DO are shown in Figure 2. The control reactors presented a mean temperature of 31.3 ± 3.2°C, whereas the LED reactor temperature was 28.6 ± 2.2°C. No significant differences were found between the reactor's temperatures (F = 6.713, p > 0.05) or within the reactors, along the operational time (F = 0.255, p > 0.05). pH ranged between 8.24 and 9.60 for control reactors, and between 8.22 and 9.60 for the reactors with LED. Mean DO values of 9.1 ± 7.8 and 9.0 ± 6.4 mg DO/L were measured for the control and LED reactors, respectively. No significant differences were detected for pH and DO within (pH: F = 2.709 p > 0.05 and DO: F = 23.395 p > 0.05) or between reactors (pH: F = 4.199 p > 0.05 and DO: F = 4.056 p > 0.05).

While temperature was an independent and not controlled variable, pH and DO were determined by biological processes. Constant pH values were accompanied by alkalinity decreases detected in both reactors. Total alkalinity consumption was 885.4 ± 7.5 mg CaCO₃ in the control reactors and 440.9 ± 113.6 mg CaCO₃ in the LED reactors. These decreases were attributed to microalgal consumption of dissolved CO₂ during photosynthesis (Park et al. 2011), as no precipitate formation or other CO₂ loss pathways occurred in the reactors. In addition, microalgal photosynthesis was probably the major cause of the tendencies observed for DO, while showing that measured concentrations were enough for holding heterotrophic activity. Oxygen consumption was observed after the addition of activated sludge containing bacterial populations, resulting in a slight decrease in DO concentrations. The concentrations of oxygen in the control reactors showed a wider variation when compared to the LED reactors. Control reactors reached maximum DO concentrations around 20 mg·L⁻¹ due to oversaturation produced by intense photosynthetic activity during hours of maximum sunlight, resulting in a high standard deviation of DO values but no significant differences when compared to LED reactors. Conversely, LED reactors exhibited smaller variations since lighting intensity and consequently the photosynthetic rates were always relatively constant.

**MICROALGAE PRODUCTION**

Chl-a concentrations were evidence that microalgae used the digestate as source of nutrients in both lighting conditions (Figure 3(a)). However, significant differences were detected within (F = 18.136, p < 0.05) and between reactors (F = 52.037, p < 0.05), whereby light conditions using LED were considerably better for microalgal biomass production in respect to solar lighting provided in control reactors. Chl-a productivity in control and LED reactors at the end of the operational period was 2.9 ± 2.1 and 31.3 ± 6.4 mg Chl-a·m⁻²·d⁻¹, respectively.
to the end of the operational period (Period II). The adaptation of *C. vulgaris* to grow on digestate and both lighting conditions was confirmed by the increases in cell counting along the acclimation and operational periods. Regarding microalgae growth, average net value for LED reactors was slightly higher than for control, i.e. $7.83 \times 10^6$ and
7.20·10^6 cell·mL^−1, respectively and more chl-a content was measured in that treatment (Figure 3(c)). These results matched with fluorescence under red light (670 LP filter) in flow cytometry, indicating that the percentage of photosynthetic organisms (Figure 3(d)) increased in the LED reactors (i.e. 57.4 ± 5.2%) and decreased in the control (i.e. 34.2 ± 12.3%). This was possibly a consequence of differences in bacteria and microalgae cell content of chlorophyll. Additionally, heterotrophic bacteria (non-fluorescing cells) seemed to increase their populations in the control, while remaining relatively constant when using LED.

More chl-a content per cell in the LED reactors suggests that algae responded to the light condition by altering their photosynthetic pigment content (Wu 2016). It is also possible that LED treatment produced changes in cell sizes since larger cells would have greater amount of chlorophyll for same net biomass quantities, but this was not verified as no measures of cell sizes were made. Cell counting and chl-a content were similar to previous values found in outdoor ponds treating wastewater with ammonia concentrations in the range of 800–1,600 mg·L^−1 and pH 8. However, chl-a content in LED reactors in our study was higher than those previously reported (Ayre et al. 2017).

Light at low intensities also seemed to promote a more energy-efficient photosynthesis compared to high PAR intensity sunlight in control reactors, which may have been closed to photoinhibition levels. Probably, the reason for this inefficiency is related to a higher photon flux density, in which the rate of photon absorption by the antenna chlorophylls exceeds the rate at which photosynthesis occurs at maximum, wasting up to 50–80% of absorbed photons (Carvalho et al. 2011). Additionally, since each strain and culture may experience photoinhibition at different intensities and culture conditions (Sorokin & Krauss 1958), our results suggest that adaptation of C. vulgaris to food waste digestate at outdoor Brazilian temperatures seemed to perform better at low artificial lighting intensities at 660 nm than at high intensities of natural sunlight. Furthermore, low intensities may represent a more cost-efficient solution for wastewater treatment in photobioreactors in respect to higher artificial lighting intensities previously reported (Yan et al. 2013; Zhao et al. 2013; Mohammed et al. 2014).

In respect to species diversity, food waste digestate showed an inhibitory effect, since original inoculum had a higher number of species, composed of Scenedesmus spp., Euglena spp., C. vulgaris, Dinobryon sp., Monactinus simplex, Botryococcus braunii, Pandorina sp., Planktolyngbya limnetica, Aulacoseira granulata, Peridinium sp., Desmodesmus sp., Trachelomonas volvocina and Microcystis aeruginosa. However, the diversity was quickly lost during the first days of the experiment. This was probably related to high ammonia concentrations in the digestate. In fact, ammonia toxicity is a main constraint on microalgae-based treatments of highly concentrated wastewater, such as observed for Scenedesmus obliquus with 534 mg NH₄Cl·L^−1 at pH 8.4 (Azov & Goldman 1982) or Neochloris oleoabundans and Dunaliella tertiolecta, inhibited at levels of 2.3 and 3.3 mg NH₃·L^−1 at pH 8.0, respectively (Gutierrez et al. 2016). However, some species may survive under high ammonia concentrations, such as Chlorella sorokiniana and Nanochloropsis oculata (Gutierrez et al. 2016), which could be a similar response observed for C. vulgaris in our experiments.

**Digestate treatment performance**

**S-COD removal**

S-COD concentrations significantly decreased along the operational period within both reactors (Figure 4(a)) (F = 81.68, p < 0.05) with final concentrations of 304.2 ± 77.1 and 84.0 ± 17.4 mg·L^−1, in control and LED reactors, respectively (F = 17.516, p < 0.05). S-COD removal efficiencies increased within reactors along the operational period (F = 10.529 p < 0.05) (Figure 4(b)) leading to final S-COD removal efficiencies of 84.0 ± 4.1% in control and significantly higher efficiencies of 95.8 ± 0.92% in LED reactors (F = 21.695, p < 0.05).

S-COD removal efficiencies above 80% were obtained in both LED and control reactors after 6 to 8 days of experiment. Higher efficiencies of S-COD removal obtained in the LED reactors suggested that the low irradiances of 15 μmol·m^−2·s^−1 did not limit microalgae-based treatment of food waste digestate and, conversely, exhibited a better performance compared to other studies in which LED lighting at higher irradiances were used (Yan et al. 2013; Zhao et al. 2013; Mohammed et al. 2014; Tricolici et al. 2014). Lighting conditions in LED reactors contributed to S-COD removal performance, since microalgae performed photoaeration for heterotrophic activity without increasing pH to maximum values unfavourable for activated sludge bacteria, while slightly higher maximum pH in control reactors may have limited heterotrophic bacterial activity (Mohammed et al. 2014).

**Nitrogen transformations**

Figure 5(a) shows the temporal series for ammonia nitrogen and Figure 5(b) a nitrogen compounds balance for initial
and final day of operational period. TAN concentrations decreased over time within reactors \( (F = 15.402, p < 0.05) \) and were significantly \( (F = 45.302, p < 0.05) \) lower in control reactors \( (74.4 \pm 48.1 \text{mgTAN·L}^{-1}) \) than in LED reactors \( (225.0 \pm 20.3 \text{mgTAN·L}^{-1}) \), which removed less ammonia \( (53.0 \pm 7.2\%) \) than control reactors \( (89.6 \pm 12.6\%) \).

The balance among different forms of nitrogen seems to be mainly influenced by ammonia volatilization and biological assimilation. Approximately 17% and 36% of TAN was transformed into \( \text{org-N} \) in control and LED reactors, respectively, whereas around 50% of TAN in control reactors and 15% in LED reactors were lost from the system and unable to be included in the nitrogen balance. The increase in the \( \text{org-N} \) fraction evidences that high ammonia levels in food waste digestate were not inhibitory for \( C. \) vulgaris, which was capable of ammonia uptake for biomass production. Higher nitrogen losses in control reactors may be attributed mainly to \( \text{NH}_3 \) volatilization caused by maximum pH values \( (>9.0) \) and temperatures \( (\sim 35^\circ C) \), which altered the \( \text{NH}_3/\text{NH}_4-N \) equilibrium to more than 50% of ammonia being present as the neutral and volatile form \( \text{(NH}_3) \) and potentially volatilized \( \text{(Emerson et al. 1975).} \) Other
mechanisms may include nitrate denitrification during nighttime when DO concentrations were low (<1 mg·L⁻¹) allowing the establishment of anoxic conditions (Park & Craggs 2011). However, nitrification was low in both treatments since a short production of NO₃-N was observed, meaning that nitrifiers were possibly inhibited by pH conditions above the optimum range (6.2-8.0) (Gujer 2010).

TAN removal accounted for 89.4 ± 12.6% in control reactors and 50.3 ± 7.2% in LED reactors. The efficiencies for nitrogen removal were relatively low when compared with other studies using or not LED lighting (e.g. Tricolici et al. 2014), but they are still results valuable since initial concentrations at food waste digestate were high and dilution was short (~30%). From a sustainable reuse perspective, TAN levels in filtered effluent and org-N in algal biomass can be positive if soil application is planned as a reuse alternative for the system’s effluent and/or energetic exploitation of biomass.

Phosphorus and TSS

Statistical analyses of PO₄-P concentrations (Figure 6(a)) revealed no significant differences either within reactors along time (F = 0.188, P > 0.05) or between reactors (F = 0.032, P > 0.05). PO₄-P consumption may have been masked by re-mineralization of total-P from organic matter in digestate or even of the algal biomass, especially in control reactors where more losses may have occurred due to temperature and lighting variations. Anyway, removal efficiencies broadly coincide with other experiences with C. vulgaris, reporting low values of about 20% for N:P ratios between 61 and 70 (Choi & Lee 2015) or not a clear tendency at all (Tricolici et al. 2014). As mentioned for TAN, phosphorus concentrations in effluent may give an agriculture value to the treated digestate, even though higher TAN removal efficiencies are required to obtain an effluent with an N:P ratio of 1:5, which would have a more interesting ratio for e.g. beans fertirrigation.

Figure 6(b) presents time variations for TSS concentrations in both reactors, which remained constant along the operational period within (F = 3.041, p > 0.05) and between reactors (F = 1.476, p > 0.05). Considering the high concentration of TSS in food waste digestate, solids were not associated with algal/bacterial biomass, even considering that biomass is a fraction of solids. No significant solids removal was expected in the microalgae-based reactors, since microalgae show low settling rates so an external mechanism like centrifugation or flocculation would be required to obtain higher solids removal efficiencies (Park et al. 2011).

Finally, both control and LED reactors inactivated TC and E. coli at similar magnitudes (Table 2). Even if final dilutions made for determinations could have been smaller, at a dilution level of 10² no presence of coliforms or E. coli was found by the end of the operational period, so reactors’ effluent would accomplish the WHO’s (2006) standard of <10³ colony forming unit/100 mL for reuse in agriculture. Mechanisms of TC and E. coli inactivation in maturation ponds and algal systems have been reported as associated with high penetration of UV radiation, elevated pH (especially pH > 10), elevated DO concentration (favouring photooxidation) (von Sperling 2002). Since pH was always lower than 10 in both control and LED reactor and no UV radiation was expected in the LED reactor, the
predominant mechanism must have been an oxidative stress produced by high DO concentrations.

**Sustainability of microalgal-based technology application to food waste digestate**

Global results of this work provide a perspective for microalgae-based reactor design and operation for increasing sustainability in treatment of sewage containing high concentrations of organic matter and nutrients, as those observed in food waste digestate. It was evidenced that microalgal productivity and economy of energy can be improved by combining solar and artificial LED lighting. In this work, PAR intensities of $15\, \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ were obtained with dimmed LED strips consuming $12.5\, \text{W}$ during HRT of 15 d and a photoperiod of 12 h, which was equivalent to an energy daily consumption of 0.15 kWh. The overall consumption was of $0.48\, \text{kWh} \cdot \text{kg COD}_{removal}^{-1}$ (or $1.875\, \text{kWh} \cdot \text{m}^{-3}$), which is considerably less than consumptions of activated sludge and/or artificial lighting at higher LED irradiances (e.g. Mohammed et al. 2013).

Furthermore, the area required for application of microalgal-based technologies could potentially be reduced by increasing reactor depth using artificial LED lighting applied under the level of the euphotic zone, which would remain illuminated by sunlight. Area requirement limit current applications of microalgae-based technologies in urban and peri-urban areas of developed and developing countries, which are the typical localization of biggest food waste sources. Thus, reducing area requirements is a decisive factor in full-scale implementation of microalgae-based technologies for sustainable treatment of food waste digestate. An example could be as follows: if a typical high rate algal pond (HRAP, reactor height $h = 0.30\, \text{m}$) treating $1\, \text{m}^{3}$ per day of food waste digestate may require an area of $33\, \text{m}^{2}$, an optimized HRAP of $h = 1.2\, \text{m}$ could reduce that requirement to $8\, \text{m}^{2}$ ($\sim 75\%$) using LED lighting at low irradiance in a depth of $0.90\, \text{m}$, provided by inner vertical panels with a PAR source producing around $400\, \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, which can easily secure minimum values around $15\, \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ in a horizontal distance of 15 cm (Mohammed et al. 2013), overcoming lighting blocking and scattering by solids. According to our results, energy consumption in such a reactor will be close to $2,000\, \text{kWh} \cdot \text{m}^{-3} \cdot \text{month}^{-1}$. Current (2018) electric energy price in Belo Horizonte is US$0.18\, \text{kWh}^{-1}$ so $\sim$US$360$ month$^{-1}$ would be required per m$^3$ of food waste treated. The cost per m$^2$ of area in Belo Horizonte is about US$2,000; thus diminishing an area of 35 m$^2$ to 8 m$^2$ implies savings of around US$50,000$, comparable to energy costs of about 12 years of operation with LED artificial lighting, which seems an economically and environmentally sustainable scenario for food waste digestate treatment, even without considering the economical values of the reuse of subproducts.

**CONCLUSIONS**

Food waste digestate with high ammonia concentrations and a C:N:P ratio of 74:74:1 showed to have an inhibitory effect on a high range of microalgae species. However, *C. vulgaris* was able to survive and perform photoaeration and assimilation of nutrients when illuminated with solar lighting in control reactors or LED lights ($660\, \text{nm}$, $15\, \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$) in the LED reactors. LED reactors exhibited a better performance in S-COD removal, with efficiencies of $95.81 \pm 0.92\%$, higher than efficiencies of $84.02 \pm 4.05\%$ obtained in the control reactors. TAN efficiencies of LED reactors were less than those obtained in the control reactors as a consequence of higher ammonia volatilization at slightly higher pH values. No significant differences between control and LED reactors were found for PO$\text{$_4$}$-P removal efficiencies. Nutrients and microbiological composition of treated food waste digestate suggest that either energetic or agricultural reuses are opportunities for increasing sustainability of food waste management. LED lighting at 660 nm and $15\, \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ is a cost-effective solution to optimize bioreactors for microalgae-based treatment of highly concentrated digestates and other wastewaters.

**Table 2** | Performance of control and LED reactors for total coliforms and *E. coli* inactivation (Ci: initial concentration; Cf: final concentration; CFU: colony forming unit)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Total coliforms</th>
<th><em>E. coli</em></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Control</td>
<td>LED</td>
</tr>
<tr>
<td>$C_i$</td>
<td>$2.8 \times 10^{5} \pm 1.7 \times 10^{5}$</td>
<td>$4.6 \times 10^{5} \pm 3.4 \times 10^{5}$</td>
</tr>
<tr>
<td>$C_f$</td>
<td>$&lt;10^2$</td>
<td>$&lt;10^2$</td>
</tr>
<tr>
<td>Removal (log-units)</td>
<td>$5.3 \pm 0.3$</td>
<td>$5.6 \pm 0.3$</td>
</tr>
</tbody>
</table>
ACKNOWLEDGEMENTS

Authors acknowledge the Minas Gerais State Agency for Research and Development – (FAPEMIG) for funding support through project 694 – FAPEMIG – APQ-02752-14 and the National Council for Scientific and Technological Development (CNPq) for the scholarship 141428/2016-3.

REFERENCES


Von Sperling, M. 2002 Lagos de estabilización. In: Lagos de estabilização. DESA/UFMG.


