Association of septic tank and sand filter for wastewater treatment: full-scale feasibility for decentralized sanitation
Luana Mattos de Oliveira Cruz, Adriano Luiz Tonetti and Bianca Graziella Lento Araujo Gomes

ABSTRACT
Worldwide, 70% of the individuals who do not have access to sanitation facilities live in rural areas. A solution for these areas is the use of decentralized systems for wastewater treatment. However, most of the studies about this topic are performed in a laboratory or in pilot scale. This work investigated a full-scale decentralized system. The association of septic tank and sand filter was installed in a rural area in Brazil. Its feasibility, maintenance, and operational conditions were appraised. The septic tank was built with precast concrete rings (inner diameter: 1.90 m; total depth: 2.34 m; useful volume: 4.30 m³). The sand filter was also constructed with precast concrete rings (internal diameter: 1.90 m; surface area: 2.84 m²) and effluent application was intermittent. The hydraulic loading rate of the sand filter was 253 Lm⁻²C₀²day⁻¹. The quality of the effluent met the legal aspects and the system proved to be effective for decentralized sanitation. The final effluent may be reused in agricultural activities; however, the frequency of maintenance of this system should be taken into account.

Key words | anaerobic treatment, decentralized sanitation, nitrification, wastewater

INTRODUCTION
The problem of sanitation in the world has been widely discussed and evidenced by the data on the accessibility and quality of sewage services. According to the report of the World Health Organization (WHO), the United Nations Children’s Fund (UNICEF) and the Joint Monitoring Programme for Water Supply and Sanitation, known as JMP, in 2012, 2.4 billion individuals had no access to improved sanitation facilities and 70% of them lived in rural areas. Moreover, one billion individuals had no sanitation facilities and defecated in open areas and the majority of these (90%) lived in rural areas. Inadequate sanitation in rural areas has been proved to affect people’s health (Kabila 2010).

Although the rural areas are scattered, there is contamination of water bodies and soil affecting the water supply and its irrigation and recreation uses. Thus, decentralized wastewater treatment systems are an interesting alternative for sanitation in rural areas.

In the USA, 10% of the generated wastewater is treated by decentralized systems (Bradley et al. 2002). This percentage represents approximately 60 million individuals, of whom 20 million have septic tanks. Australia is similar with 12% of the population using septic tank systems to treat wastewater (Massoud et al. 2009).

Even though septic tanks are widely used as decentralized treatments, there is a need for the post-treatment of
their effluent. This is because the effluent still has a high content of soluble organic matter and pathogens (Witkovski & Vidal 2009).

Tonon et al. (2015) studied intermittent sand filter (ISF) systems as anaerobic post-treatment. The combination between anaerobic filter and sand filter enabled an efficiency exceeding 95%, which produced an effluent that meets the Brazilian and European legislation (Conama 357 2005; Directive 91/271/CEE). The results showed that ISF systems are reliably able to achieve a significant reduction in chemical oxygen demand (COD), total suspended solids (TSS), coliform bacteria and viruses (Darby et al. 1996; Emerick et al. 1999). The degree of possible treatment using an optimized ISF system is comparable to the secondary and tertiary treatment systems, thus enabling the disinfection and reuse of the water (Asano et al. 2007; Leverenz et al. 2009; Marinho et al. 2015; Leonel et al. 2016).

Although the importance of this type of treatment is known, most of the studies have been performed in a laboratory or in pilot scale (Stevik et al. 1999b; Healy et al. 2007; Kang et al. 2007; Sabbah et al. 2013; Tonon et al. 2015) and only a few studies have been developed in full scale (Pell et al. 1990; Zhang et al. 2005; Li et al. 2011). Due to those aforementioned reasons, this study aimed to develop and investigate the full-scale combination of septic tank and sand filter to verify its feasibility, maintenance, and operational conditions.

**METHODS**

This research was developed in an area located in the rural municipality of Campinas, Brazil, during 7 months (from July 2012 to February 2013). The land was occupied by a construction company (Villa Stone Campinas), three residences, and one small business. Regarding the company, only the wastewater generated in the bathrooms was used in the study. Throughout the research, the small treatment plant received a daily contribution from eight to ten individuals.

The treatment consisted of an association of septic tank and sand filter (Figure 1). The septic tank was built with precast concrete rings. The inner diameter was 1.90 m and total depth was 2.34 m. The useful volume of the reactor was 4.30 m³, and the theoretical hydraulic retention time (HRT) was 2 days, but after starting the operation, the real HRT was 1.6 days. There were two internal baffles (Figure 1): one in the entrance and another one in the exit to guide the sewage in the septic tank, preventing its short circuit (ABNT 1993).

The liquid leaving the septic tank was directed to a square siphoned box with width of 0.30 m and useful volume of 0.025 m³ (Figure 2). As the input flow was lower than the output flow of the siphoned box, the adoption of this provision was enabled at the intermittent application of effluent in the sand filter (next stage of the effluent).
Moreover, even when peak flows occurred (when the residents showered or used the kitchen or bathroom sinks), the septic tank behaved like a damping tank of input flow. Thus, the effluent outflow from the septic tank had only a small variation and the flow that reached the siphoned box was small and relatively uniform. This allowed the box to be filled to the limit of the siphoning process. Meanwhile, the sand filter did not receive the effluent and was naturally aerated. After complete filling of the siphon box, the siphoning process was initiated and all the liquid was quickly applied in the sand filter surface. Subsequently, the filling of the siphon box started again and, consequently, the infiltration of the liquid applied to the sand filter and its aeration. Thus, the aerobic characteristic of this sand bed was ensured.

The sand filter (Figure 3) was constructed with precast concrete rings with internal diameter of 1.90 m, which allowed a surface area of 2.84 m². For the composition of the bed, three layers stratified from the reactor base were used and their description is shown in Figure 3 and Table 1. These characteristics were measured by the authors. The volume of effluent produced was compared to the volume of water consumed in the study site. Both flows were measured by a commercial hydrometer installed in the field (Itron – flodis S analog – minimum flow: 15 L h⁻¹).

Effluent samples were collected weekly from the septic tank and sand filter (Figure 1). The standard deviations were calculated using the results of the 7-month samples. No replicate was performed during this study and the frequency of sampling was based on other pilot and full-scale studies (Tonetti et al. 2012; De Oliveira Cruz et al. 2013; Tonon et al. 2015). The 2-liter samples were collected during the morning period (the set time was at 8 o’clock) and stored at 4 °C (box temperature). Immediately after all samples were collected, they were taken to the laboratory where analysis was performed based on Standard Methods for the Examination of Water and Wastewater (APHA et al. 2012).

Assessment of the phosphorus in the sand

In order to determine the phosphorus adsorption capacity limit for the sand used in the research, a test was carried out based on the work of Sovik & Klove (2005). An assessment was made of the sand before placing it in the sand filter.
(Anew) and after clogging (Aclogged). The procedures for both sand samples (Anew and Aclogged) are schematized in Table 2.

For the test with Anew, a solution of concentration equal to 50 mgL\(^{-1}\) was prepared with KH\(_2\)PO\(_4\) (potassium dihydrogen phosphate). An aliquot of 50 mL of this solution was added to a flask containing 20 g of sand (dry weight) and then mixed for 24 hours on a shaker. After this, the supernatant liquid was analyzed for phosphorus concentration. The data obtained were analyzed by applying Equation (1) (Sovik & Klove 2005):

\[
q = \frac{(C_0 - C) \cdot V}{m}
\]

where \(q\) is the phosphorus absorption coefficient (mg g\(^{-1}\)), \(C_0\) is the initial concentration of the solution (mgL\(^{-1}\)), \(C\) is the final concentration of the supernatant (mgL\(^{-1}\)), \(V\) is the volume of the solution (L), and \(m\) is the dry weight of the sand sample (g). This equation was just applied for the new sand. The clogged sand phosphorus concentration was analyzed by the supernatant of digestion.

In the Aclogged sample, the adsorbed phosphorus concentration was evaluated after its use as filter material. The sample was obtained from the surface layer of the sand bed after clogging. The solid sample (20 g of dry weight sand sample) was digested in the procedure. Then the supernatant was removed and filtered through paper with porosity of 0.45 μm. The resulting filtrate was evaluated regarding phosphorus concentration.

### RESULTS AND DISCUSSION

Over the 7 months of study (from July 2012 to February 2013), we found that there was an average consumption of 1,901 ± 160 L\(\cdot\)day\(^{-1}\) of potable water in the site where the treatment system was installed. The per capita consumption ranged between 190 and 237 L\(\cdot\)person\(^{-1}\)\(\cdot\)day\(^{-1}\), since the number of people living in the area varied from eight to ten during the research period.

This value is very close to that found in the urban area of the municipality in which the research was conducted. In this case, the city of Campinas (Brazil) has an average consumption of 231.5 L\(\cdot\)person\(^{-1}\)\(\cdot\)day\(^{-1}\) (SNIS 2017). This may indicate that currently the populations of rural areas located in the vicinity of urban areas, can have the same consumption of water as those living in urban areas since there is the same water availability (the water was provided by the sanitation company).

However, the relationship between water consumption and generation of wastewater was much lower than that traditionally found in urban areas, which can reach 80% in Brazil (ABNT 1986). According to Mara (2004), the return factor, which is the fraction of water consumed that becomes wastewater, is usually 0.8–0.9. In the study area, this relation

<table>
<thead>
<tr>
<th>Material</th>
<th>Depth (m)</th>
<th>Effective size (D(_{10}) (mm))</th>
<th>Uniformity coefficient (UC)</th>
<th>Void ratio (V(_r)) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravel 2</td>
<td>0.20</td>
<td>16.12</td>
<td>1.89</td>
<td>45.80 ± 0.40</td>
</tr>
<tr>
<td>Gravel 1</td>
<td>0.05</td>
<td>7.51</td>
<td>1.66</td>
<td>44.08 ± 0.38</td>
</tr>
<tr>
<td>Sand</td>
<td>0.40</td>
<td>0.18</td>
<td>3.14</td>
<td>28.58 ± 0.87</td>
</tr>
</tbody>
</table>

**Table 2** | Steps to characterize the sands regarding their phosphorus concentration

<table>
<thead>
<tr>
<th>Before placement in the sand filter (Anew)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample 20 g + 50 mL of KH(_2)PO(_4) solution (Concentration: 50 mgL(^{-1}))</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>After clogging (Aclogged)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample 20 g</td>
</tr>
</tbody>
</table>
was only 38%. This value was lower than expected because the Brazilian population living in rural areas uses wastewater from washing machines and the washing of internal and external floors for the irrigation of gardens and fruit trees.

Thus, there was an average production of wastewater of 717 ± 50 L day⁻¹. Consequently, the hydraulic loading rate of the sand filter studied was 253 ± 18 L m⁻² day⁻¹. This figure was higher than the rate recommended by the Brazilian standard that regulates the construction of this treatment system (ABNT 1997). It indicates that the hydraulic loading rates for the septic tank effluent should not exceed 100 L m⁻² day⁻¹. The USEPA (2002) recommended hydraulic loading rates range between 80 and 200 L m⁻² day⁻¹.

Therefore, even if it received higher hydraulic loading rates than the Brazilian and American standards, the sand filter could operate, producing a high quality effluent, as discussed in the following section.

Moreover, we observed that the period of wastewater generation occurred between 8:30 am and 8:30 pm. Thus, the hydraulic loading rate in the sand filter during that 12-hour period amounted to 506 ± 36 L m⁻² day⁻¹. This showed that the system was able to receive much higher hydraulic loading rates than that established by the Brazilian and American standards.

This result demonstrates the effectiveness of the system and confirms the pilot-scale experiments of Tonetti et al. (2012) and Tonon et al. (2015). Both authors worked with hydraulic loading rates above 400 L m⁻² day⁻¹ and obtained an effluent that met the legal aspects.

Physical-chemical analysis

The average air temperature of the days at the moment the samples were collected was 24.1 ± 4.5 °C.

The pH values of the effluent from the septic tank and sand filter were close to neutral values (Table 3). The alkalinity found in the septic tank effluent (536 ± 75 mg CaCO₃L⁻¹) was much higher than the typical values of domestic wastewater (60 to 120 mg CaCO₃L⁻¹) reported by Metcalf & Eddy Inc. (2005). Moreover, it was also higher than that found for anaerobic effluents. For example, Musereere et al. (2014) obtained an alkalinity of 271 ± 17 mg CaCO₃L⁻¹ for an effluent from primary settling tanks, and De Oliveira Cruz et al. (2013) found an average value of 300 ± 100 mg CaCO₃L⁻¹ for an effluent from anaerobic filters.

A possible explanation for this behavior may be associated with the low dilution of the existing wastewater in systems that treat wastewater in small communities. As earlier stated, in Brazil, the rural population traditionally reuses some of the wastewater generated in a residence in the irrigation of gardens and fruit trees. Thus, the domestic wastewater generated will be basically from bathrooms and kitchens, and therefore more concentrated in terms of ammoniacal-N and total nitrogen (95 ± 29 and 166 ± 110 mg L⁻¹, respectively). This justifies the higher alkalinity of the wastewater.

The COD of the sand filter effluent was 106 ± 59 mg O₂ L⁻¹. The limit stipulated by the legislation in the European Community (Directive 91/271/CEE) for discharges from urban wastewater treatment plants (WWTPs) is 125 mg O₂ L⁻¹. Although it is used for urban WWTPs, it is an important limit to consider. Thus, the system under study ensured the adequacy of the wastewater on this parameter (75% of the samples were below this limit).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Septic tank (mean ± standard deviation)</th>
<th>Sand filter (mean ± standard deviation)</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>7.0 ± 0.2</td>
<td>7.0 ± 0.2</td>
</tr>
<tr>
<td>Alkalinity (mg CaCO₃L⁻¹)</td>
<td>536 ± 75</td>
<td>503 ± 50</td>
</tr>
<tr>
<td>TSS (mg L⁻¹)</td>
<td>196 ± 33</td>
<td>24 ± 18</td>
</tr>
<tr>
<td>Turbidity (NTU)</td>
<td>219 ± 195</td>
<td>9 ± 5</td>
</tr>
<tr>
<td>E. coli (NMP 100 mL⁻¹)</td>
<td>1.18 × 10⁶ ± 1.04 × 10⁶</td>
<td>2.56 × 10⁶ ± 1.81 × 10⁶</td>
</tr>
<tr>
<td>COD (mg CaCO₃L⁻¹)</td>
<td>359 ± 103</td>
<td>106 ± 59</td>
</tr>
<tr>
<td>BOD (mg CaCO₃L⁻¹)</td>
<td>286 ± 82</td>
<td>21 ± 8</td>
</tr>
<tr>
<td>TKN (mg L⁻¹)</td>
<td>166 ± 110</td>
<td>114 ± 27</td>
</tr>
<tr>
<td>N-NH₄ (mg L⁻¹)</td>
<td>117 ± 15</td>
<td>95 ± 29</td>
</tr>
<tr>
<td>Nitrate (mg CaCO₃L⁻¹)</td>
<td>4 ± 3</td>
<td>14 ± 10</td>
</tr>
</tbody>
</table>
et al. (1996), tested bed thicknesses between 0.31 and 1.63 m and hydraulic head of only 76 Lm$^{-2}$day$^{-1}$ of wastewater. In that experiment, the authors found BOD in the effluent of the shallower filter of 11.0 mgL$^{-1}$ and of the deeper filter of 2.5 mgL$^{-1}$. They concluded that depths greater than 0.90 m did not impact the treatment. In Ireland, Rodgers et al. (2011) used hydraulic loading rate of 105 Lm$^{-2}$day$^{-1}$. The influent had a BOD of 241 mgL$^{-1}$ and the effluent 30 and 50 mgL$^{-1}$, for 0.3 and 0.4 m deep filters.

Comparatively, in this study we applied hydraulic loads of 253 Lm$^{-2}$day$^{-1}$, which is approximately 3.3 and 2.4 times greater than used by Widrig et al. (1996) and Rodgers et al. (2011), respectively. However, the results obtained for the BOD in the effluent from sand filters were extremely close to those of the aforementioned authors. As in a sand filter, not only physical but also various chemical and biochemical reactions take place; the treatment performance is dependent on the temperature thus foreign standards should not be the principal influence of the design of this system in hot climate countries, like Brazil. Hot countries need to undertake new research about this kind of wastewater treatment system to find new conditions to project these systems.

In rural areas, the low concentration of suspended solids found in the effluent from the sand filter (24 ± 18 mgL$^{-1}$) would be beneficial for reuse in agriculture. There would be a lower possibility of clogging of the irrigation equipment used, such as the dripper. Capra & Scicolone (1998) claimed that there was a low risk of clogging of drippers when the final concentration of the TSS is less than 50 mgL$^{-1}$. The average value is also less than the limit stipulated by the legislation in the European Community (Directive 91/271/CEE) for discharges from urban WWTPs (35 mgL$^{-1}$).

As a result of the removal of the suspended solids, turbidity removal efficiency was also high. The sand filter generated an effluent with mean of 9 ± 5 NTU. Regarding the density of Escherichia coli, the removal given by the sand filters was 2-log units (Table 3), which is comparable to the removal found by Tonon et al. (2015) for sand filters and by Saliba & Von Sperling (2017) in activated sludge systems. These values associated with small turbidity value would allow the elimination of these organisms, indicators of fecal contamination, with the use of low chlorine doses.

We highlight the great capacity of sand filters in oxygenating the effluent from the septic tank. On average, the effluent produced had a dissolved oxygen (DO) concentration of 5.0 ± 1.5 mgL$^{-1}$. This value is higher than the DO concentration found in anaerobic effluents (less than 1 mgL$^{-1}$) and is within the limit to discharge in water bodies, according to Brazilian National Environment Council (CONAMA 450 2011). This aeration of the effluent was caused by the intermittent operation of the sand filter. This shows that there is great aeration of the effluent even with the adoption of a simplified siphon system (Figure 2). If there was no intermittent application, DO concentration would be as low as values found for anaerobic effluents (Tonon et al. 2015).

The performance of the nitrification (12% of total Kjeldahl nitrogen (TKN)) was low compared to other studies by Healy et al. (2007), Rolland et al. (2009), and Tonetti et al. (2012). This fact could be due to the lower depth of the sand bed. The value of 0.40 m was adopted in this study while Tonetti et al. (2012) used 0.75 m and obtained a complete nitrification of the nitrogen compounds.

However, in an attempt to understand the evolution of the treatment of the effluent along the infiltration in a sand bed, Pell & Nyberg (1989) collected samples at various depths, starting from the surface, of various sand filters. The authors concluded that the nitrification occurred rapidly and within a few centimeters from the bed surface. No significant changes were found below 15 cm in the concentrations of nitrogen compounds. A similar experiment was conducted by Ellis (1987), who found that 50% of the nitrification and removal of solids also took place on the surface layer.

Bahgat et al. (1999) also demonstrated the importance of the surface layer of sand filters when they noted that the time spent by the nitrifying bacteria to reach the balance of their activities near the surface was similar to that spent throughout the system until stabilization. Thus, the literature does not indicate that the adopted depth is an adequate explanation for the lower efficiency of the nitrification achieved in this full-scale study.

According to Tonon et al. (2015), the aeration of the biofilm is enhanced by longer periods between applications of anaerobic effluents in the sand filters as a result of the greater diffusion of oxygen into the biofilm structure, thus ensuring good nitrification efficiency. According to Stevik et al. (1999a), smaller hydraulic loading rates allow a greater
exchange between mobile pore water fractions and those with less mobility as well as a prolonged contact between the biofilm growing over the solid phase and pollutants. There are also increments in the duration of the endogenous decay phase (Leverenz et al. 2009) and partial recovery of the filter porosity.

With higher hydraulic loading rates, water infiltration was swifter, and the exchange between the mobile pore water fractions and those with less mobility was reduced (Stevik et al. 1999a). Gradually, the oxygen supply was also reduced, in this way threatening the sustainability of the nitrification process (Tonon et al. 2015).

When the feeding sequences were short and the bed surface was no longer submerged after each of these sequences, the volumetric supply of convective fresh air could be as high as the volume of the infiltrated water (Bancolé et al. 2003). Due to these factors, a greater nitrification may take place at low hydraulic loads and a drop can be perceived at higher values (Tonon et al. 2015; Magalhães et al. 2016).

As discussed, the treatment system received contributions mainly between 8:30 am and 8:30 pm. Even in this time interval, the wastewater flow occurred with greater intensity in the morning (after breakfast and morning shower) and in the afternoon (after preparing dinner and evening shower). Therefore, in these cases, the successive applications from the siphoned box could prevent a proper interaction between the effluent and the microbiota responsible for nitrification.

**System maintenance**

During the research, three operations to clean the surface of the sand beds were necessary. This was due to the problem of clogging of the surface layer of the reactor. The maintenance of the bed required only the scraping of a 0.05 m layer of its surface, which enabled the full restoration of the proper functioning of the treatment system.

This result is consistent with the statements of Rodgers et al. (2005) and Kristiansen (1981). These authors noted that the loss of infiltration was mainly related to the first 0.02 m of the bed and was the result of retained solids and microbial growth. The rest of the bed remained almost unchanged. Rice (1974) noted that 80% of the structure of a sand filter did not change even after 3 years of activity.

On average, 10 weeks elapsed until the clogging. It is important to highlight that the literature on the use of this treatment system does not provide a discussion regarding the time required for this maintenance. Leverenz et al. (2009) mention that there is a paucity of data relating surface clogging and operational parameters because clogging was generally not the desired outcome or the focus of the copious amount of ISF research studies that have been conducted.

In this way, the treatment system comprised by the association of septic tank and sand filter is very efficient regarding the physical and chemical parameters, and it produces treated water suitable for reuse. However, there is a need for routine maintenance. This maintenance does not inhibit the spread of this technology, but it should be clearly understood by the community that will build it and operate it.

**Phosphorus retention in the sand bed**

The sand filter provided an average phosphorus removal efficiency equal to 53.8% but with a downward trend throughout the operating time (Figure 4). Over the weeks, there was a tendency in the increase of the phosphorus concentration in the effluent until reaching the clogging of the sand bed after approximately 10 weeks. However, we noted a higher phosphorus concentration in the effluent than in the influent from the 7th week of the study.

One possible explanation for this behavior is the formation of anaerobic conditions in the interface between the sand and the effluent. This may have favored the release of phosphorus in the water column. Thus, a process might
be happening based on ‘luxury uptake’ and ‘overplus accumulation’, which express the ability of a biological sludge, submitted to cyclic anaerobic/aerobic conditions, in accumulating phosphorus in excess in relation to its necessities in the presence of oxygen (Levin & Shapiro 1965; Converti et al. 1995).

After each clogging, there was the removal of the surface layer of the bed and its replacement with new sand. This action favored the recovery of a high phosphorus removal. Again, this capability decreased over the weeks. Thus, the increasing concentration of phosphorus in the effluent can be a chemical indication of the existence of the clogging of the sand bed.

Comparatively, the USEPA (1980) found that the reduction in the concentration of this compound can reach percentages of up to 50% in filters recently put into operation. According to this agency, there is a loss of efficiency during the maturation of the bed.

In the assessment of the sand made before placing it in the sand filter (A<sub>new</sub>) and after clogging (A<sub>clogged</sub>), we observed that the phosphorus adsorption capacity of A<sub>clogged</sub> is much higher than that found in A<sub>new</sub> (Table 4). This can be an indication that the main factor that leads to the phosphorus removal in this type of treatment would not be the chemical adsorption capacity of the sand, as described in the literature (Arias et al. 1999; Jokela et al. 2002; Rodgers et al. 2005; Sovik & Klove 2005). Possibly, the incorporation into the biofilm is the mechanism that predominates in the phosphorus removal process.

CONCLUSIONS

The association of septic tank and sand filter is a viable technology for decentralized sanitation, mainly in rural areas.

The quality of the effluent generated may allow its reuse in agricultural activities. However, the frequency of maintenance of this system should be taken into account. Thus, users’ acceptance of the systems should be investigated to show whether any education or training is necessary and the users’ perception of the required maintenance task.

Throughout the use of the sand filter, there is a downward trend in the phosphorus removal efficiency until the clogging of the surface of the sand bed. Possibly, the phosphate adsorption capacity of the sand bed was not mainly from the chemical adsorption of the sand, but from the incorporation into the biofilm.

ACKNOWLEDGEMENTS

The authors would like to thank CNPq (the Brazilian National Council for Scientific and Technological Development, Processo 471853/2011-8) for the scholarships granted, in addition to FAPESP (São Paulo Research Foundation, Process 2017/07490-4) and Villa Stone Campinas for financing this study. The authors would also like to acknowledge the service of the Writing Space/General Coordination of UNICAMP for helping translate the original manuscript.

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