

## Treatment of effluent from the coconut (*Cocos nucifera*) processing industry via dissolved air flotation

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### Abstract

The coconut palm (*Cocos nucifera* L) is one of the most widespread fruit species worldwide and plays a key role in Brazilian agribusiness, especially in the Northeast, which accounts for over 90% of national production. However, coconut processing generates large volumes of liquid effluents, composed of coconut milk, oil, and mainly washing water, which require proper treatment before disposal. Among the available techniques, dissolved air flotation (DAF) stands out for its efficiency and low operating cost in contaminant removal. This study focused on treating coconut industry effluents using DAF, applying a full 2<sup>3</sup> experimental design. The evaluated factors were effluent concentration (0.05% and 0.1%), feed flow rate (100 L/h and 150 L/h), and dilution flow rate (50 L/h and 100 L/h), with initial pH fixed at 10 and saturation pressure between 4.5 and 6 kgf/cm<sup>2</sup>. Aluminum sulfate 1% m/v was used as the coagulant. Results showed that oil and grease reduction increased with higher effluent concentration and lower dilution flow rates, reaching up to 73.75% removal under conditions of 0.1% concentration, 150 L/h feed, and 50 L/h dilution.

**Keywords:** flotation, coconut, effluent treatment, oil and grease, coagulation, factorial design.

## Tratamento de efluentes da indústria de processamento de coco (*Cocos nucifera*) por flotação por ar dissolvido

### Resumo

O coqueiro (*Cocos nucifera* L.) é uma das espécies frutíferas mais difundidas no mundo e desempenha papel fundamental no agronegócio brasileiro, especialmente na região Nordeste, responsável por mais de 90% da produção nacional. Entretanto, o processamento do coco gera grandes volumes de efluentes líquidos, compostos por leite de coco, óleo e, principalmente, água de lavagem, os quais necessitam de tratamento adequado antes do descarte. Entre as técnicas disponíveis, a flotação por ar dissolvido (FAD) destaca-se pela eficiência e baixo custo operacional na remoção de contaminantes. Este estudo teve como objetivo o tratamento de efluentes da indústria do coco utilizando FAD, aplicando um planejamento experimental completo 2<sup>3</sup>. Os fatores avaliados foram concentração do efluente (0,05% e 0,1%), vazão de alimentação (100 L/h e 150 L/h) e vazão de diluição (50 L/h e 100 L/h), com pH inicial fixado em 10 e pressão de saturação entre 4,5 e 6 kgf/cm<sup>2</sup>. Sulfato de alumínio a 1% m/v foi utilizado como coagulante. Os resultados demonstraram que a redução de óleos e graxas aumentou com maior concentração do efluente e menores vazões de diluição, alcançando até 73,75% de remoção nas condições de 0,1% de concentração, 150 L/h de alimentação e 50 L/h de diluição.

**Palavras-chave:** flotação, coco, tratamento de efluentes, óleos e graxas, coagulação, planejamento fatorial.

## 1. Introduction

Coconut (*Cocos nucifera* L.) is a tropical crop widely cultivated due to the multiple industrial applications of its products and by-products, including coconut water, copra, coconut oil, raw kernel, coconut cake, coconut toddy, shell-based materials, coir, and other derivatives (DebMandal; Mandal, 2011). According to the Food and Agriculture Organization of the United Nations (FAO, 2024), global coconut production reached approximately 62.4 million tons in 2024, with Indonesia, the Philippines, and India occupying the leading positions, while Brazil remained among the major producers (Viana et al., 2026).

In addition to its relevance in primary production, Brazil occupies a strategic position in the global coconut processing chain, particularly in the coconut water sector. The Centre for the Promotion of Imports from Developing Countries highlights Brazil as a pioneer in the international coconut water market and one of the largest industrial processors, supported by a supply chain focused on green coconuts for beverage consumption (CBI, 2025). Recent market estimates also indicate strong sectoral expansion, with the global coconut water market valued at approximately USD 4.43 billion in 2024 and the Brazilian market projected to grow substantially in the coming years (Grand View Research, 2026). This industrial expansion contributes significantly to the economy but also generates substantial volumes of agro-industrial effluents requiring appropriate treatment.

Effluents generated during coconut processing are typically characterized by high organic load, elevated concentrations of oils and grease, suspended solids, turbidity, and biodegradable compounds. If discharged without adequate treatment, these wastewaters may cause serious environmental impacts, including oxygen depletion in receiving water bodies, eutrophication, deterioration of water quality, and ecological imbalance in aquatic ecosystems (Adetunji; Olaniran, 2021; Abuhasel et al., 2021). Due to the complex composition and oily nature of these agro-industrial effluents, efficient treatment strategies are essential to minimize environmental damage and ensure regulatory compliance.

Conventional treatment methods for oily agro-industrial effluents include biological treatment, membrane separation, coagulation-flocculation, adsorption, chemical oxidation, and other physicochemical processes (Crespilho et al., 2004). Although these technologies can be effective, many present limitations such as high operational costs, membrane fouling, sludge generation, and operational complexity, particularly when treating wastewater with elevated oil and grease content (Musa; Idrus, 2024). In this context, dissolved air flotation (DAF) has emerged as a promising alternative due to its operational simplicity, rapid separation efficiency, relatively low energy demand, and high effectiveness in removing hydrophobic contaminants.

DAF is a physicochemical treatment process in which wastewater is saturated with air under pressure and subsequently depressurized, generating microbubbles that attach to suspended solids and oily compounds, promoting flotation and separation from the liquid phase (Plumier et al., 2026). This technique has demonstrated satisfactory performance in the treatment of oily industrial effluents due to its operational flexibility and efficient contaminant removal (Muñoz-Alegría et al., 2021).

Despite the recognized applicability of DAF for wastewater treatment, studies specifically focused on coconut-processing effluents remain scarce, particularly regarding the evaluation of operational conditions for total oil and grease removal. Most available investigations focus on municipal wastewater or other agro-industrial sectors. For example, Santos et al. (2025) evaluated DAF as a post-treatment system for anaerobic municipal effluent and reported satisfactory removal of physicochemical contaminants. However, the distinct composition of coconut-processing wastewater, especially its elevated lipid content, represents a specific challenge that remains insufficiently explored in the literature.

Therefore, this study aimed to evaluate the efficiency of dissolved air flotation in the treatment of coconut-processing effluents by investigating the influence of operational conditions on total oil and grease (TOG) removal, in order to assess the feasibility of DAF as a treatment strategy for this agro-industrial wastewater.

## 2. Materials and Methods

### 2.1 Stages

The study was divided into two stages: identification of the best conditions (coagulant volume and pH) for fat coagulation, and a study of floc separation in the dissolved air flotation column.

A synthetic effluent from the coconut processing industry was used, prepared by adding 0.1% and 0.05% w/v of coconut milk to water. The coconut milk used is from the SOCOCO brand, containing 3 grams of total fat and 2.7 grams of saturated fat.

### 2.2 Study of coagulation conditions in a jar test

The jar test consists of equipment fitted with 3 or 6 reactors (cups), in which coagulation/flocculation tests are performed simultaneously. Through a mechanical or electromagnetic system, it causes agitation (mixing) in the cups at the same time, at the speed desired by the operator. In this work, the “jar-test”, brand POLICONTROL (Figure 1), was used.

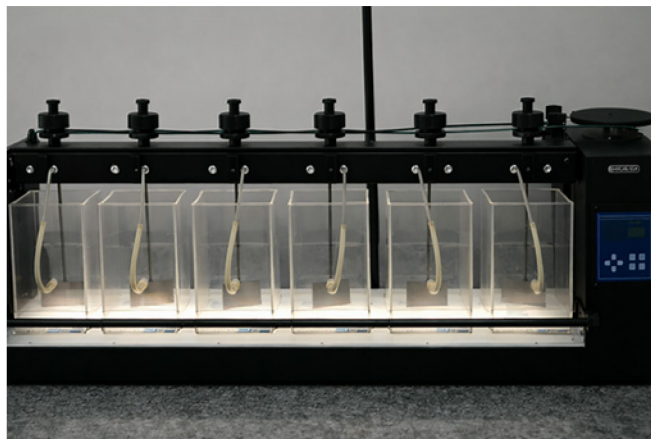


Figure 1. Jar test apparatus. Source: Authors, 2026.

This study aimed to identify the optimal pH and dosage of aluminum sulfate coagulant, prepared in a 1% w/v solution.

Two jar tests were performed, one for the effluent with a concentration of 0.1% and the other for the effluent with a concentration of 0.05%, separately. The same procedures were followed in both tests. One liter of synthetic effluent contaminated with coconut milk was placed in each jar. A different pH was chosen for each jar, ranging from 6 to 11. In jar 1, the pH = 6, in jar 2, the pH = 7, in jar 3, the pH = 8, in jar 4, the pH = 9, in jar 5, the pH = 10, and in jar 6, the pH = 11.

During the test, the stirring speed was maintained at 20 rpm, and 5 mL of the coagulant (aluminum sulfate) was added every 5 minutes. At the end of the tests, it was observed that the coagulant performed best in the jar with a pH of 10 for both concentrations. For the effluent prepared with 0.1% coconut milk, the amount of coagulant needed for optimal clarification was 25 mL, while for the effluent with a concentration of 0.05%, optimal clarification was achieved with 20 mL of coagulant.

### 2.3 Experimental races

First, a complete  $2^3$  experimental design was carried out, investigating the influence of the following factors: effluent concentration (0.05 and 0.1% w/v); synthetic effluent feed flow rate (100 and 150 L/h), and dilution flow rate (50 and 100 L/h) on the reduction of TOG. The dilution flow rate refers to the water flow rate used to generate microbubbles. The limits associated with each variable are represented in (Table 1). The lower limit is represented by -1 and the upper limit by +1.

Table 1. Levels of parameters used in the full factorial design.

Level	Effluent concentration (%)	Feed flow rate (L/h)	Dilution flow rate (L/h)
-1	0.05	100	50
+1	0.1	150	100

Source: Authors, 2026.

The experimental matrix for the 2<sup>3</sup> design is presented in (Table 2).

Table 2. Experimental design matrix.

Experiment	Effluent concentration	Feed flow rate	Dilution flow rate
1	-1	-1	-1
2	+1	-1	-1
3	-1	+1	-1
4	+1	+1	-1
5	-1	-1	+1
6	+1	-1	+1
7	-1	+1	+1
8	+1	+1	+1

Source: Authors, 2026.

The experiments were performed in duplicate (a total of 16) and in a random order; the numbering does not correspond to the order in which the experiments were performed, and in each experiment, the reduction in TOG was analyzed.

In the study of dissolved air flotation, a pilot unit was used, consisting basically of a 140-liter feed tank; a flotation cell (pressurized vessel for generating micro-bubbles); three centrifugal pumps, two operating in series to feed the flotation cell and the other to feed the column; a peristaltic pump for adding the coagulant; a compressor tube for injecting air into the pressure vessel; rotameters for measuring feed and air flow rates; and the column itself, as shown in (Figure 2). The unit was operated in an open circuit to prevent changes in the concentration of the feed tank.

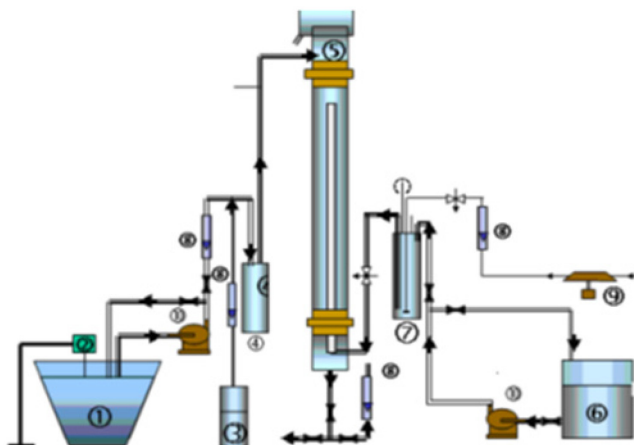


Figure 2. Diagram of the pilot unit for dissolved air flotation. Note: 1 Effluent, 2 Agitator, 3 Coagulant, 4

Flocculation Tank, 5 Flotation Column, 6 Recycle Tank, 7 Pressure Tank, 8 Rotameter, 9 Compressor, 10 Positive Displacement Pump. Source: Santos et al. (2010).

The flotation unit consists of a column made up of two concentric vertical tubes with a circular cross-section, constructed of acrylic. The column operated in a countercurrent configuration, with the effluent feed coming from the side, just below the top of the column. Dissolved air was added at the base of the column, inside the inner tube. The treated effluent was removed at the base of the column, in the annular region between the inner wall of the column and the outer wall of the inner tube. The flocs were collected through a collector located at the top of the column.

The bubble generation unit consists of: a water tank; a compressor; a positive displacement pump; and a stainless steel pressure vessel, measuring 13.5 cm in internal diameter and 50 cm in height, equipped with a pressure gauge and level indicator.

For the generation of microbubbles, water was injected into the pressure vessel at different predetermined flow rates, thus diluting the treated effluent (dilution water).

Simultaneously, compressed air was fed into the vessel, directly into the liquid phase, maintaining the pressure in the vessel between 4.5 and 6.0 kgf/cm<sup>2</sup>, dissolving the air in the water until saturation. In reality, bubble generation begins to occur from 4.0 kgf/cm<sup>2</sup>, showing better production between 4.5 and 5.0 kgf/cm<sup>2</sup> (Soletti et al., 2004).

The effluent was prepared directly in the feed tank by mixing coconut milk and water. For a 0.05% concentration effluent, 70 grams of coconut milk were added, and for a 0.1% concentration, 140 grams were added to 140 liters of water, feeding the top of the flotation column. This was done after the in-line addition of the flocculating agent, using a peristaltic pump with flow rates of 2.5 and 3.75 L/h, for feed flow rates of 100 and 150 L/h of the coagulating agent (Al<sub>2</sub>SO<sub>4</sub>), respectively. Samples were collected from the feed (raw effluent) and from the equipment outlet (treated effluent).

#### *2.4 Determination of total oil and grease (TOG) content*

TOG determination was performed according to Silva (2009). Oil and grease content analysis was performed using the infrared energy absorption technique, in the wavelength range between 3.4 and 3.5 micrometers. It was determined in ppm using a HORIBA OCMA-350 oil analyzer (Figure 3). According to the principle of this instrument, the amount of energy absorbed is directly proportional to the concentration of oil present in the sample. As water also absorbs energy in the 3.4 and 3.5 micrometer range, the extraction of oil present in the samples was carried out using a solvent mixture of 2,2,4-iso-octane, ketone, and chlorobenzene, in a volumetric ratio of 3:3:2, which, in addition to being insoluble in water, does not absorb energy in this wavelength range.

A 60 mL sample was transferred to a filtration funnel, and 50 mL of solvent was added. The mixture was shaken and left to stand until two visually distinct phases formed: one phase composed mainly of water, and the other, the heavier phase, of solvent and oil. After the phases separated, the (oil + solvent) phase was filtered in the presence of anhydrous sodium sulfate to absorb any remaining water droplets and prevent interference with the analysis results. After filtering the entire phase, the solution was shaken and analyzed, using the solvent as a standard for the "zero" point.

### **3. Results**

#### *3.1 Results of the coagulation conditions study*

The coagulant aluminum sulfate showed the best performance at pH 10. Therefore, all experimental runs were conducted at this pH.

During the test, the 0.1% coconut milk solution showed the best clarification when 25 mL of the 1.0% aluminum sulfate solution was added. For the 0.05% concentration, the required volume was approximately 20 mL of 1.0% aluminum sulfate.

During the test, the fragility of the formed flocs was observed, which were broken at a low agitation speed (20 rpm). The increase in kinetic energy impaired the formation of the flocs.

The addition of the coagulant reduced the pH of the solution to levels below 4, which may have impaired floc formation, since the optimal pH range for aluminum sulfate is between 5 and 8. In the jar test, for an initial

effluent pH of 10, the addition of the coagulant lowered the pH to approximately 5, which is close to the range presented in the literature for the best action of aluminum sulfate.

### 3.2. Results from experimental races

In the experimental unit, the formation of microbubbles, used for floc separation, was achieved by maintaining the pressure between 4.5 and 6 kgf/cm<sup>2</sup> (pressure vessel) to dissolve the air in the water, followed by a rapid depressurization at the inlet of the flotation column, forming a mist at the outlet of the central feed tube (Figure 4).

Operating with a higher effluent feed flow rate (150 L/h) hindered floc formation, probably due to agitation caused by the effluent entering the column, since the flocs formed are fragile. A solution to this problem is to operate with the column level above the feed zone, which reduces system agitation.

Another problem encountered was the clumping of bubbles at the base of the column. Some of the bubbles that enter the system end up at the bottom of the column, due to the treated effluent discharge zone. Some of the flocs formed adhere to the bubbles and end up exiting along with the treated effluent. This causes the column to have a slightly whitish color at the base, become white in an intermediate zone, and yellowish at the top, due to the higher concentration of flocs (Figure 3).



Figure 3. Aspect created inside. Source: Authors, 2026.

Comparisons between the raw effluent, the treated effluent, and the top product are shown in (Figures 4 and 5). Note that the treated effluent has a slightly whitish color, due to the presence of fine flocs and, mainly, the high amount of dissolved oxygen, due to the process.



Figure 4. Comparison between treated effluent (left side) and synthetic effluent (right side). Source: Authors, 2026.



Figure 5. Comparison between the treated effluent (right side) and the product from the top of the column (left side). Source: Authors, 2026.

### 3.3 Results of TOG analyses

Table 3 below presents the average values of oil and grease content for the raw effluent and the treated effluent, as well as the results of the percentage reductions obtained in the sixteen experimental runs. The last column (reduction) corresponds to the decrease in TOG, comparing the synthetic effluent to the treated effluent.

Table 3. Results of TOG reduction.

Experiment	Ce (%)	Qf (L/h)	Qd (L/h)	Initial TOG (mg/L)	Final TOG (mg/L)	Reduction (%)
1	0.05	100	50	32.15	17.90	44.48
2	0.1	100	50	33.85	14.00	58.64
3	0.05	150	50	42.40	32.30	23.82
4	0.1	150	50	53.90	14.15	73.75
5	0.05	100	100	18.15	6.80	62.81
6	0.1	100	100	51.55	23.35	54.70
7	0.05	150	100	15.50	14.10	9.35
8	0.1	150	100	55.45	31.50	43.19

Note: Ce is the effluent concentration; Qf, the feed flow rate; Qd, the dilution flow rate. Source: Authors, 2026.

Experiment 4 (effluent concentration of 0.1%, feed flow rate of 150 L/h, and dilution flow rate of 50 L/h) obtained the greatest reduction in TOG (73.7%). The second-best result was obtained in experiment 5 (62.8%), which operated with an effluent of 0.05%, a feed flow rate of 100 L/h, and a dilution flow rate of 100 L/h. The smallest reduction, 9.3%, was obtained for the effluent with a concentration of 0.05%, a feed flow rate of 150 L/h, and a dilution flow rate of 100 L/h (experiment 7), Table 3.

In general, a significant reduction in TOG was obtained, especially for the lower dilution flow rates, 50 L/h. This occurred because the volume of saturated water was smaller and the pressure maintained by the compressor was uniform throughout all experimental runs, causing a greater amount of air to enter the column, resulting in the flocs floating.

It can also be observed in Table 3 that, except for experiments 3 (effluent concentration of 0.05%, feed flow rate of 150 L/h and dilution flow rate of 50 L/h), 6 (effluent concentration of 0.1%, feed flow rate and dilution flow rate of 100 L/h) and 8 (effluent concentration of 0.1%, feed flow rate of 150 L/h and dilution flow rate of 100 L/h), all the others obtained TOG lower than the 20 mg/L required by state decree nº 6.200/1985.

Due to the significant difficulty in analyzing the effects resulting from the interaction between the variables studied in the flocculation process, a full 23 factorial design was used, considering 3 variables (effluent concentration, feed flow rate, and dilution flow rate) channeled at two extreme levels, resulting in 8 experiments performed in duplicate.

The Statistica 10.0 software was used to calculate the effects. All results are within the 90% confidence range.

The main effects and interaction effects between the variables were calculated. The effects represent the influence that each variable exerts on the system's response (reduction of TOG). Table 4 shows the main effects and interaction effects.

Table 4. Main and interaction effects.

Main Effects	
1 (Effluent concentration)	22,45
2 (Feed flow rate)	-17.63
3 (Dilution flow rate)	-7.66
Interaction Effects	
12	19.43
13	-9.59
23	-14.85

Source: Authors, 2026.

Significant effects were observed: variation in effluent concentration, feed flow rate, and the interactions between effluent concentration and feed flow rate, and between feed flow rate and dilution flow rate.

According to Table 4, when the effluent concentration increases from 0.05% to 0.1%, the effect is positive, meaning that increasing the effluent concentration results in a greater reduction in TOG. This was expected because a higher effluent concentration, which has a greater amount of oil, leads to the formation of larger flocs, resulting in a greater reduction.

Table 4 shows that increasing the feed flow rate from 100 L/h to 150 L/h leads to smaller reductions in TOG, as does increasing the dilution flow rate from 50 L/h to 100 L/h. With a feed flow rate of 150 L/h, there were no significant reductions. This is due to the low floc formation resulting from the low concentration, and the fragility of these formed flocs, combined with the agitation caused by the high flow rate, breaking them apart.

For the interaction between feed flow rate and dilution flow rate, Table 4, an increase in flow rates leads to smaller TOG reductions, and the interaction between effluent concentration and dilution flow rate leads to lower yields when these variables move from the lower level (0.05% and 50 L/h) to the upper level (0.1% and 100 L/h).

For the interactions, observing Table 4, an increase in effluent concentration, even with an increase in feed flow rate, leads to greater TOG reductions, showing that the effect of effluent concentration is more significant than

the effect of feed flow rate.

#### 4. Discussion

The results demonstrated that dissolved air flotation significantly reduced oil and grease concentrations in synthetic coconut-processing effluent, confirming the technical feasibility of this treatment method for oily agro-industrial wastewater. The highest removal efficiency (73.75%) was obtained under conditions of higher effluent concentration (0.1%), intermediate feed flow rate (150 L/h), and lower dilution flow rate (50 L/h). This suggests that greater contaminant loading may favor larger floc formation, enhancing bubble-particle attachment and flotation efficiency.

The positive effect of effluent concentration corroborates classical flotation theory, in which higher concentrations of hydrophobic particles increase collision probability between contaminants and microbubbles. Conversely, increasing the feed flow rate negatively impacted separation efficiency in several experiments, likely due to increased turbulence causing floc breakage and reduced bubble adhesion stability.

The dilution flow rate also influenced treatment performance. Lower dilution rates may increase effective air saturation efficiency and improve microbubble generation under constant pressure conditions. The fragility of flocs observed experimentally suggests that improved coagulation optimization may further enhance removal performance. Although aluminum sulfate showed satisfactory performance, alternative coagulants such as ferric chloride, polyaluminum chloride, or bio-based coagulants could be investigated in future studies.

Compared with other oily wastewater treatment techniques, DAF offers operational simplicity, short hydraulic retention time, and relatively low energy demand. However, this study employed synthetic wastewater under controlled laboratory conditions, which may not fully represent the complexity of real industrial coconut-processing effluents. Future work should investigate pilot-scale continuous operation, additional pollutant parameters (COD, turbidity, TSS), economic feasibility, and integration with biological post-treatment systems.

#### 5. Conclusions

The present study demonstrated that dissolved air flotation (DAF) is a promising and efficient technique for the treatment of coconut-processing effluents, especially regarding the removal of oils and grease. The experimental results confirmed that the operational parameters evaluated significantly influenced treatment performance. Higher effluent concentrations associated with lower feed and dilution flow rates promoted greater removal efficiencies, indicating the importance of process optimization in flotation systems.

Under the operational condition of 0.1% effluent concentration, 100 L/h feed flow rate, and 50 L/h dilution flow rate, oil and grease removal efficiencies exceeded 70%, highlighting the applicability of DAF for oily agro-industrial wastewater treatment. The use of aluminum sulfate as a coagulant also contributed positively to contaminant separation and flotation efficiency.

In addition to its high removal performance, DAF presents important advantages such as operational simplicity, rapid treatment, and relatively low operating costs, making it a viable alternative for the coconut-processing industry. Therefore, the findings of this study contribute to the advancement of sustainable strategies for agro-industrial effluent management and provide technical support for future investigations involving process optimization, pilot-scale studies, and integration with complementary wastewater treatment technologies.

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#### 7. Authors' Contributions

*Victor Cesar Pugliesi de Sousa, Tiago Marques da Silva, and Tiago Lima Alves:* conceptualization, investigation, experimental execution, formal analysis, data curation, visualization, and writing—original draft preparation. *Júlio Inácio Holanda Tavares Neto, José Harlisson de Araújo Ferro, and Amanda Santana Peiter:* methodology, validation, supervision, data interpretation, and writing—review and editing. *Sandra Helena Vieira de Carvalho and João Inácio Soletti:* conceptualization, methodology, formal analysis, supervision, validation, project

administration, and writing—review and editing.

## 8. Conflicts of Interest

No conflicts of interest.

## 9. Ethics Approval

Not applicable.

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