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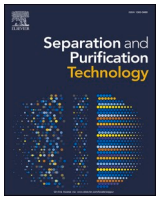

Techno-Economic analysis of an efficient anthocyanin extraction process from grape pomace using eutectic solvents — A critical panorama regarding drying techniques and reusability of solvents

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ABSTRACT

A techno-economic analysis of a novel eutectic solvent-based platform useful to recover anthocyanins from grape pomace was performed. The study addressed the economic impact of conventional drying methods and explored the economic implications of purification strategies to separate the extract from the eutectic solvent. This was exemplified by employing solid-phase extraction (SPE) with C18-based adsorbent material. An alternative low-energy demanding approach using SiO_2 particles was also assessed for profitability as a freeze-drying replacement strategy. The results highlighted challenges in the economic feasibility of eutectic solvent reusability when conventional SPE is applied, highlighting the need to obtain new and inexpensive bio-based adsorbents. Moreover, it was uncovered that the SiO_2-based drying strategy presents itself as a financially viable alternative, effectively addressing the elevated energy requirements associated with conventional drying methods. The findings highlight the potential of alternative solvents-based processes, particularly towards challenges related to the circularity of raw materials.

1. Introduction

Considering the 17 Sustainable Development Goals (SDGs) preconized by the United Nations in 2015, there is a vision for a sustainable future [1]. However, to achieve these goals, it is necessary to transition from a linear to a circular economy [2], highlighting the significance of collaborative efforts between governments, businesses, and other stakeholders to accelerate this transition [3]. Over the last few years, the rapid growth of the global economy has led to an increase in solid waste generation, exacerbating social inequity status [4]. Consequently, converting residues into profitable raw materials is an excellent alternative for mitigating environmental impacts while generating employment opportunities and reducing pollution, energy consumption, and carbon emissions [5]. Within this context, we should realize that approximately 33% of the food produced worldwide goes to waste or is lost [6]. Hence, establishing integrated manufacturing platforms to recover natural compounds and create novel bioproducts from this waste emerges as a promising strategy. Such an approach fosters a green economy and paves the way for realizing a responsible society [7].

Producing wine and grape-based products is prominent in the global agro-industrial sector, making it a leading industry. The International Organization of Vine and Wine reported that in 2020, over 7 million tons of grapes were produced, as per their most recent data [8]. However, along with its prominence comes a set of environmental challenges, as this industry contributes to a significant environmental impact. For example, approximately 200 kg of solid waste is generated *per* 750 L of

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wine produced [9]. Each year, making wine and grape-based products generates approximately 18.5 million tons of solid residues, thereby emerging as one of the primary waste sources within the sector [10,11]. Nonetheless, grape pomace exhibits substantial economic and nutritional potential, mainly due to its abundance of bioactive compounds, especially anthocyanins. These compounds have drawn the interest of various sectors [12], positioning grape pomace as a desirable alternative to explore within the context of fuel for a green economy.

However, it is important to acknowledge that the manufacturing process often fails to balance sustainability and economic considerations [13], undermining the prospects outlined by the SDGs for the coming years. In a capitalist society, the profitability of a manufacturing process takes precedence, often leaving little room for the adoption of the most sustainable production methods. Hence, it is imperative to implement the principles of SDG 12 (responsible production and consumption) to pave the way for a future green economy. Additionally, within this perspective, the concept of biorefinery aligns perfectly. This concept entails exploring alternative solutions that can replace, or at the very least reduce, our dependence on fossil fuels. It needs changes in the behavior of both producers and consumers while ensuring a sustainable supply of consumer goods to society under the 3Rs principle – Reuse, Reduce, and Recycle [14]. Moreover, this vision aligns with the principles of a bio-economy, where waste mitigation plays a crucial role in achieving a sustainable society [15].

Most operational manufacturing processes traditionally adhere to a linear economic model, where technologies and reagents are used conventionally. Industrial manufacturing processes, including extracting bioactive compounds from natural sources, commonly rely on fossil fuels and Volatile Organic Solvents (VOSs). Despite their efficiency, these solvents pose environmental and health risks that must be mitigated [16]. As a more environmentally friendly alternative, water has become a safer solvent for extracting natural compounds [17]. Eutectic solvents frequently change the solute's affinity to water. Eutectic solvents are mixtures of two or more pure compounds for which the eutectic point temperature is below an ideal liquid mixture, presenting significant negative deviations from ideality [18]. Additionally, some authors have recognized eutectic solvents as high-performance solvents, which is justified by their ability to improve the extraction performance (yield of extraction) compared to processes involving conventional VOSs, while increasing their chemical stability [19]. However, applying eutectic solvents comes with uncertainties, namely their cost and challenges in their reuse. Overcoming this drawback would be possible if the eutectic solvent could be easily separated from the solid extract by applying heat, which is not the case [20], namely when bioactive compounds susceptible to temperature are focused. Therefore, it is evident that the development of eutectic solvent-based extraction/separation platforms depends on developing technologies that effectively allow them to be separated from the solid extract. As a result, research and evaluations addressing the technical and economic aspects are eagerly anticipated and highly encouraged.

The simulations presented in this study involved three distinct scenarios, each incorporating various strategies for eutectic solvent reusability and exploring novel drying techniques for the final extract. This aspect, particularly the drying methods, has not been thoroughly explored in the existing literature. The simulation investigated in the present work focused on the process developed by some of us in the last year [21]. In our earlier publication, we underscored that opting for eutectic solvents over volatile organic solvent (VOS)-based extractions not only improved the extraction performance, leading to elevated yields of anthocyanins but also facilitated a low-carbon footprint process. Furthermore, it was demonstrated that loading the anthocyanin-rich extract into SiO_2 particles, as an alternative form of drying, improved the shelf-life of the pigments and reduced both the cost and environmental impact compared to traditional spray drying methods. Thus, the present study delves into valuable insights concerning the potential feasibility of alternative extraction processes to ascertain that the previously established process is not solely environmentally advantageous but also economically viable. Specifically, we focus on those utilizing eutectic solvents and alternatives to drying the extracts, thereby laying the groundwork for extensive discussions regarding their techno-economic industrial potential.

2. Material and methods

2.1. Process simulation model

The simulations were conducted based on the technical information provided by de Souza Mesquita et al. (2023) [21]. Fig. 1 illustrates a detailed step-by-step process followed by the authors. **Step I**, involved acquiring the grape pomace from a juice industry in Limeira (São Paulo, Brazil). Then, in **step II**, a solid–liquid extraction was performed using eutectic solvents. The operational variables included an ultrasonic-assisted extraction (UAE) using an ultrasonic probe with a power output of 240 W and a frequency of 20 KHz. The solid–liquid ratio (SLR) was fixed at 0.03 $g_{biomass}.mL^{-1}_{solvent}$, with a static time of 25 min and a UAE time of 4 min. The eutectic solvents consisted of 40% w/w of water and 60% w/w of nicotinamide and acetic acid (fixed molar ratio of nicotinamide to acetic acid of 1:1). In **step III**, the anthocyanin-rich extract was obtained, still containing the eutectic solvent. To recover the eutectic solvent and purify the extracted anthocyanins, **step IV** involved a solid-phase extraction (SPE) was performed. The operational variables for this step were optimized as follows: first, the adsorbent material was activated by washing it with ethanol (using a mass ratio of absorbent:ethanol 1:5) and then conditioned with water in the same proportion. The anthocyanins were loaded into the adsorbent material at a mass ratio of absorbent:extract 1:4. Subsequently, the eutectic solvent was recovered by washing the system with water, using a volume eight times the initial volume of the extract. After completing **step IV**, two different approaches were investigated for drying the extract. In **step V**, an alternative drying method was proposed using an adsorbent material composed of SiO_2 (mass ratio SiO_2:extract 1:7), which has been approved for use as an adjuvant in the pharmaceutical, food, and cosmetic sectors. It is important to highlight that **step V** required a low-energy input (on a lab scale, it is performed by manual shaking, and on an industrial scale, a simple homogenizer system performs it). In contrast, **step VI** proposed the conventional freeze-drying method (conventionally known as a high-energy demanding technique). Finally, the dried anthocyanins (solid-state) obtained in **step VII** are considered a ready-to-market product.

The techno-economic analysis was simulated under three different scenarios. In **Scenario I**, the focus was on marketing the eutectic solvent extract absorbed into SiO_2, which involved steps I, II, III, V, and VII (Fig. 1), as illustrated in the flow diagram presented in Fig. 2A. **Scenario II**, on the other hand, focused on marketing the anthocyanins in a solid state by absorbing the extract (without eutectic solvent) into SiO_2, the latest serving as a carrier material. This Scenario encompassed steps I, II, III, IV, V, and VII of Fig. 1, with the corresponding flow diagram depicted in Fig. 2B. Lastly, **Scenario III** differed from Scenario II by replacing the carrier material with a freeze-drying step. This Scenario involved steps I, II, III, IV, VI, and VII of Fig. 1, as shown in the flow diagram of Fig. 2C. The detailed original flowsheet provided by the simulation software is depicted in Supplementary Material (Figures S1, S2, and S3).

2.2. Economic evaluation

2.2.1. Parameters

The economic evaluations were performed using the SuperPro Designer 10.0® software (Intelligen Inc., Scotch Plains, NJ, USA). The costs of manufacturing can be determined by considering the total of the main costs, which include direct, fixed, and general expenses. To estimate the costs of manufacturing, the methodology proposed by Turton

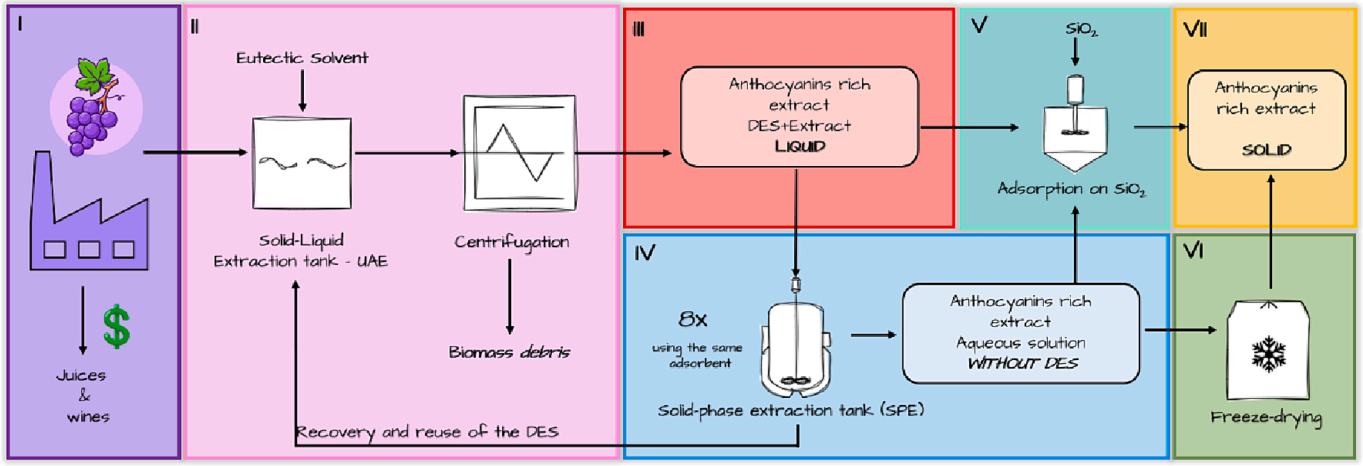

Fig. 1. Schematic representation of the evaluated steps for the three different economic scenarios: **Scenario I** – steps I, II, III, IV, V, and VII; **Scenario II** – steps I, II, III, IV, V, and VII; **Scenario III** – steps I, II, III, IV, VI, and VII.

et a. (2008) [22] was adopted, which assesses the three main components of the costs of manufacturing (COM) for each process section in terms of fixed capital of investment, cost of operational labor, cost of utilities, cost of waste treatment and cost of raw materials.

Fixed capital of investment comprises expenses associated with setting up the production line, including the extraction plants and other necessary equipment. Quotations and costs for the equipment needed to perform the extraction and purification steps were obtained from reputable vendors and previous works. However, it is essential to note that these costs pertain to lab-scale equipment and may not accurately represent the values required for industrial scaling. Thus, to achieve a more reliable price considering the equipment scale-up, Eq. (1) was applied, where C_1 represents the equipment cost with capacity Q_1, C_2 is the general base cost of the equipment with capacity Q_2, and n is a constant that depends on the equipment type. The specific values of n were collected from the literature. The base costs for the plant to extract anthocyanins from grape pomace are presented in Table S1 Supplementary Material.

$$C_1 = C_2 \times \left(\frac{Q_1}{Q_2}\right)^n \quad (1)$$

Operational labor costs are related to the operators responsible for running the extraction and purification units, as well as those performing the equipment maintenance. For this study, one or two workers (depending on the Scenario) were considered (Table S2 Supplementary Material). The cost of utilities considers the energy consumed during the UAE procedure and maintains the flow of extraction and purification of the anthocyanins, along with refrigeration and electricity requirements at each step. The raw material cost represents the expenses of obtaining the starting materials to produce the eutectic solvent (nicotinamide, acetic acid, and water) and those required to perform the SPE, including the C_{18}-adsorbent material and the SiO_2. Lastly, the waste treatment cost was considered zero since the waste produced in this process is deemed harmless and clean, thereby not requiring any pre-treatment to avoid contaminants. Moreover, in Scenarios II and III, the raw materials employed, namely the eutectic solvent and C_{18}-adsorbent material, are reused in new extraction processes for up to eight extraction cycles. Both direct (including expenses related to buildings, electrical facilities, yard improvement, insulation, instrumentation, installation, etc.) and indirect costs (these encompassing engineering and construction, administration rates, insurance, human resources for administration, cleaning services, etc.) were estimated using the simulator and included in the economic evaluation. The combination of direct costs and fixed capital of investment represents the total capital investment for the entire plant.

2.2.2. Scale-up

Considering that using probe systems (UAE) on a large scale is challenging, we opted to simulate a horizontal approach (UAE vessels side-by-side) as an excellent option to reduce energy expenditure and guarantee the same extraction yield as obtained on a lab scale. The simulation in this study considered five UAE vessels operated in batch regimes in parallel, as described in Fig. 2A–C. The same extraction conditions depicted in de Souza Mesquita et al. (2023) [21] were simulated by the SuperPro 10.0 software. The scale-up criteria for UAE were to keep constant the solid-to-liquid ratio (0.03 $g_{biomass}.mL^{-1}_{eutectic\ solvent}$) and the specific energy (4728 J. g^{-1} – the same energy as the lab scale), and for SPE and absorption using SiO_2, the ratio between extract and adsorbents was considered. It was then assumed that the extraction yield and composition of the pigment-based extracts on a large scale would be the same as those obtained on the lab scale. The sequence of activities for each Scenario simulated is presented in Tables S3, S4, and S5 provided in the Supplementary Material. The processes were designed to run for 7920 h *per* year, corresponding to three daily shifts for 330 days.

2.2.3. Profitability analysis

Information about financial return for the three studied scenarios was provided to evaluate the impact of the selling price of the three products on the payback time. The payback time represents the time needed for the total capital investment, comprising the Fixed Capital of Investment (FCI) and working capital, to be precisely balanced by the accumulative net profits. It is calculated by dividing the capital investment charged by the annual net profit. Therefore, the selling price of the three products was estimated using the SuperPro 10.0 software to attend payback times of 2.5, 5, 10, and 15 years.

3. Results and discussion

3.1. Economic evaluation

3.1.1. Impact of different production scenarios on costs of manufacturing and productivity

The production of anthocyanins-rich extract from grape pomace was simulated in SuperPro® considering three different scenarios, as highlighted in Fig. 2. The results obtained from this simulation are shown in Figs. 3-6. Adopting Ultrasonic-Assisted Extraction (UAE) technology resulted in notably superior extraction efficiency for anthocyanins compared to other methods like stirring, maceration, and ultra dispersion, as demonstrated in previous research [21]. This supports the decision to opt for a UAE process over simpler techniques. To minimize the energy demands associated with ultrasound technology, the process was

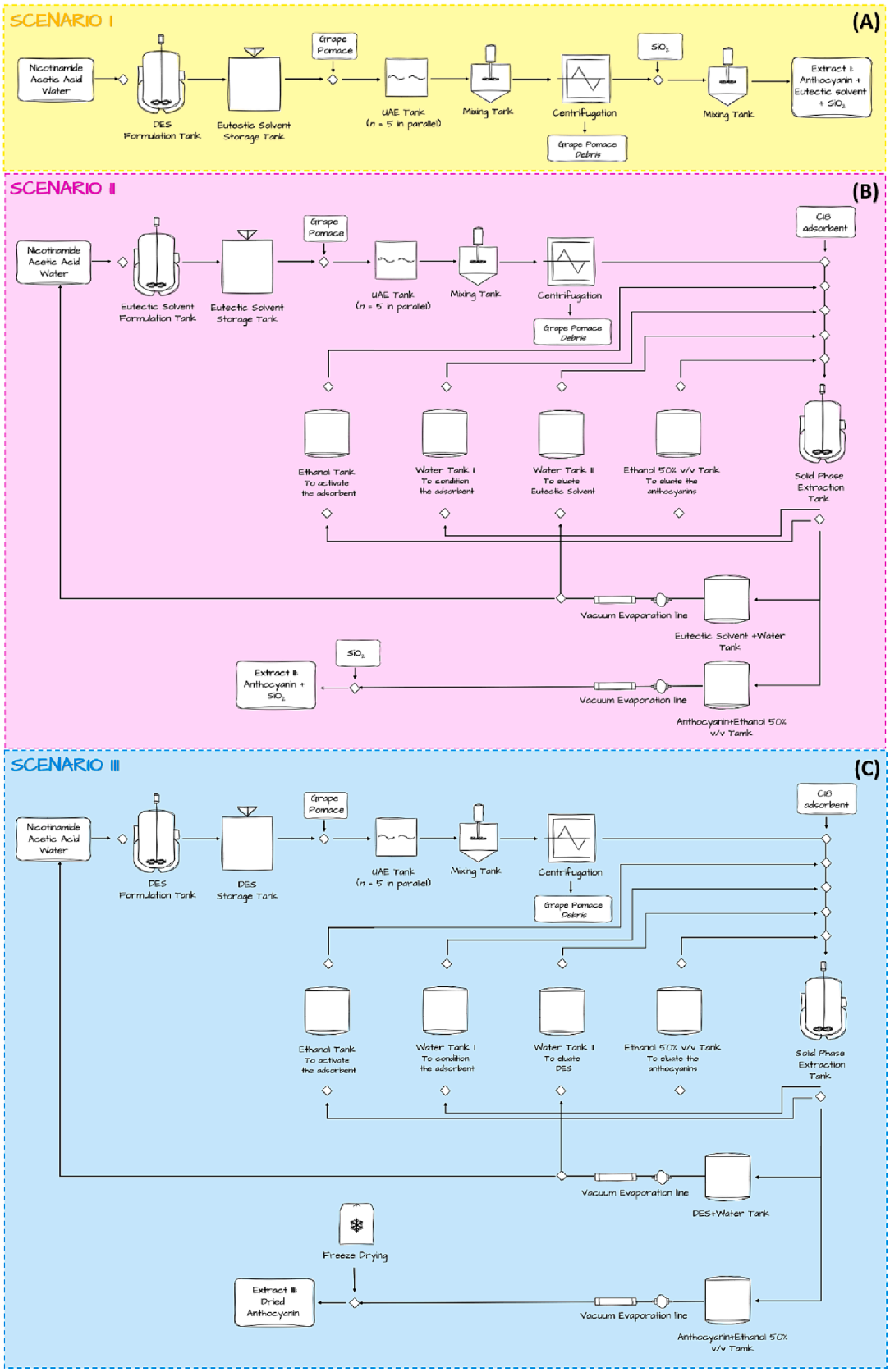

Fig. 2. Summarized flowsheet of Scenario I – obtaining a crude anthocyanin-rich extract with DES and dried with SiO_2 **(A)**; Summarized flowsheet of Scenario II – obtaining a polished anthocyanin-rich extract dried with SiO_2 **(B)**; Summarized flowsheet of the Scenario III – obtaining a polished anthocyanin-rich extract dried using a conventional, freeze drying, without using SiO_2 **(C)**. DES: Eutectic Solvent is composed of nicotinamide and acetic acid (molar ratio 1:1), and it has 40% m/m of water content. The complete flowsheet obtained from the SuperPro Software is depicted in the Supplementary Material (Fig. S1, S2, and S3).

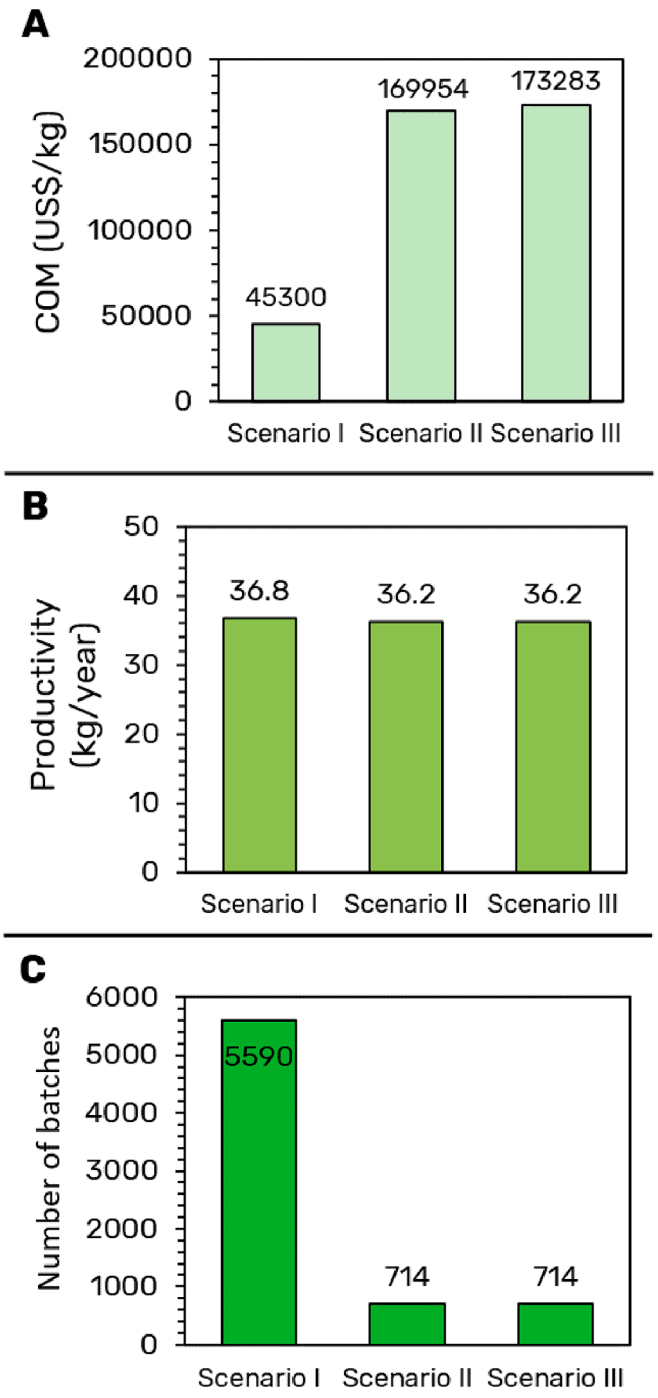

Fig. 3. Impact of the production scenarios on the costs of manufacture (COM) (A), annual productivity (B), and yearly number of batches (C).

optimized to be executed within a four-minute timeframe, dependent on ultrasound application, which assisted in mitigating the environmental impact of this process (low-carbon footprint). However, it is essential to acknowledge certain drawbacks of the UAE process. Notably, the operation of ultrasonic equipment generates approximately 65 dB of noise [23]. To tackle this challenge, it is necessary to integrate a sound shield into the system, incurring an extra cost for the process. Given this consideration, we have factored in a UAE device with this shield in the simulation approach presented in this study (Table S1 supplementary material).

Fig. 3A shows the manufacturing costs of the three scenarios, indicating that scenarios II and III provided 3.7- and 3.8- times higher manufacturing costs, respectively, than Scenario I. Fig. 3B shows the annual productivity for all three scenarios, which remains unchanged regardless of the Scenario. Lastly, Fig. 3C illustrates the number of annual batches. These three response variables (costs of manufacturing, productivity, and the number of batches) are interconnected; manufacturing costs represent the yearly total cost divided by productivity, which means the cost to produce each kilogram of the product [24]. Productivity directly depends on the number of annual batches. At this point, it is crucial to provide essential information: each batch in Scenario I corresponds to a single load of raw material in the five UAE extractors, while each batch in Scenarios II and III represents eight loads of raw material in the five UAE extractors. As a result, even though there is a difference in the number of batches between Scenarios I and II/III, the total number of annual loads of raw material in the UAE extractors remains similar. Hence, the productivity of anthocyanins does not significantly differ between the three scenarios (Fig. 3B). However, the manufacturing cost does not have the same behavior, which can be attributed to the distinct production characteristics. Scenario I has a reduced number of operations when compared to Scenarios II and III. For example, Scenarios II and III include additional steps such as SPE and solvent reusing, while Scenario III involves a freeze-drying step. Consequently, Scenarios II and III entail higher expenses for equipment, labor, raw materials, and energy, leading to an increase in the costs of manufacturing. Indeed, the higher manufacturing costs in Scenarios II and III can be attributed to the more significant equipment park required for solvent reuse. Another point worth emphasizing is the distinction between the adsorbents used. SiO_2 particles serve primarily as an alternative to spray drying, and they are used solely at the end of the process of drying the extract. In contrast, the C_{18} adsorbent, utilized in both Scenarios II and III, plays a crucial role in purifying anthocyanins from the eutectic solvent. After purification, two approaches are possible: in Scenario II, the extract, now free from the eutectic solvent, can be dried using the SiO_2-based strategy; whereas in Scenario III, conventional spray drying is employed.

Those scenarios raise an important question that manufacturers must address promptly: *Is adopting the circularity of raw materials, which may involve a higher initial investment, financially viable and environmentally sustainable in the long term?* Additionally, *does the potential profit from this approach justify the efforts to achieve environmentally friendly metrics?* These questions require careful consideration, especially given government authorities' increasing emphasis on sustainability requirements. For example, the European Union plans to prohibit the use of synthetic pigments in the food sector by 2030 [25]. Thus, finding (natural) alternatives is essential to ensure we do not end up with colorless foods! Considering these circumstances, it becomes crucial to find choices that effectively reduce costs and minimize environmental impacts, aligning them with the sustainability goals without compromising the profits. Transitioning from conventional to alternative practices may present challenges, but it is imperative to engage in thorough discussions to swiftly find viable solutions, as the demand chain will not stop. As the world continues to handle environmental challenges, embracing green manufacturing becomes an obligation and an opportunity for economic growth and prosperity. Countries can advance toward a more sustainable and resilient manufacturing sector through collaborative efforts and effective policies [26].

In addition, it is essential to highlight that the products resulting from the three scenarios differ significantly. In Scenario III, the product consists of a highly concentrated powder of anthocyanins, achieved by evaporating and freeze-drying the ethanolic extract after SPE. In Scenario II, the extract is not freeze-dried. However, it is incorporated into a silicon material composed of SiO_2 (which is a very cheap material, as can be observed in its impact on the cost of manufacturing in Fig. 4). On the other hand, Scenario I generates an anthocyanin extract with eutectic solvent, which can either be incorporated into SiO_2 or sold in a liquid state along with the eutectic solvent. Thus, it is evident that the products could be marketed for different values (Scenario II $\geq$ Scenario III $>$

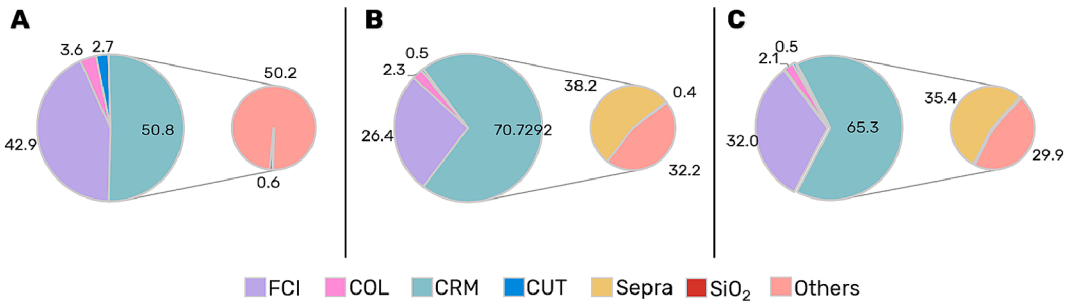

Fig. 4. Definition of costs of manufacturing (COM) for the three different production scenarios: (A) Scenario I; (B) Scenario II; and (C) Scenario III. In A, B and C, the pie chart on the left comprises fixed capital of investment (FCI), cost of operational labor (COL), cost of raw material (CRM), and cost of utilities (CUT), while the pie chart on the right comprises Sepra $C_{18}E$, SiO_2, and other components of cost of raw material (CRM).

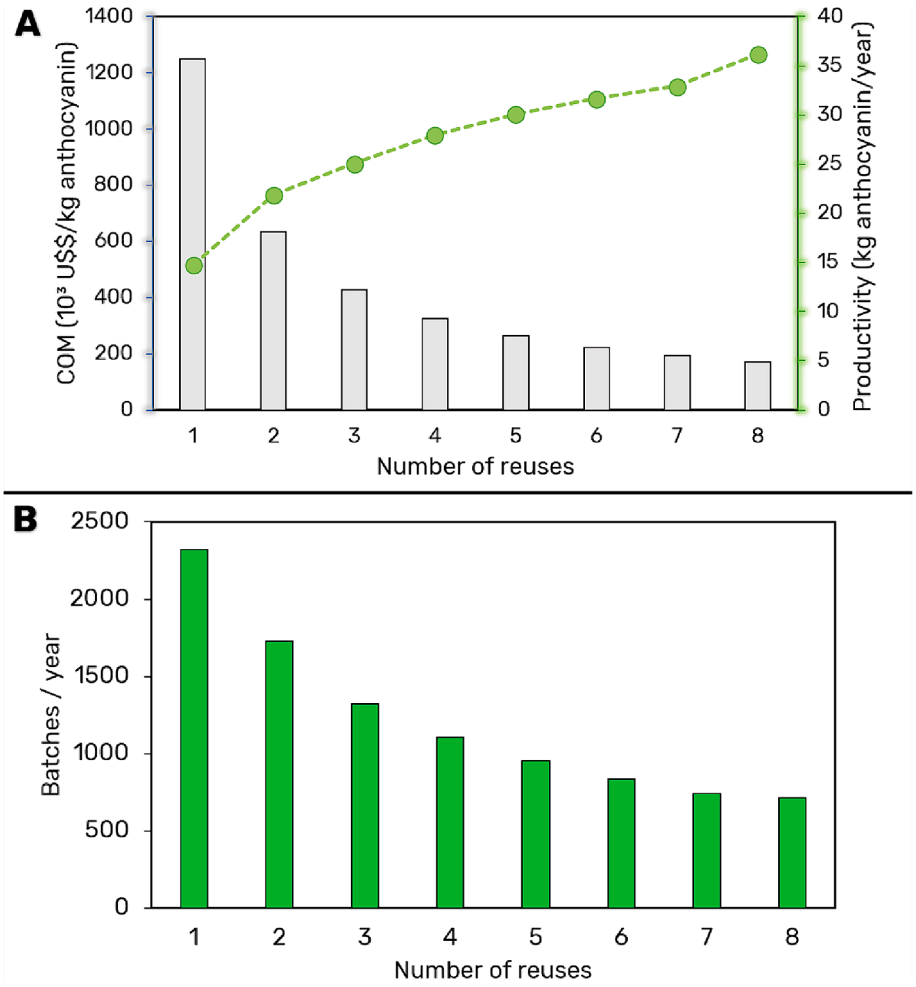

Fig. 5. Effect of the number of reuses of Sepra $C_{18}E$ adsorbent on the costs of manufacturing (COM) and productivity (**A**) and batches *per* year (**B**) simulated for Scenario II.

Scenario I), and consequently for differing commercial sectors.

Moreover, these three distinct scenarios yield extracts with significantly higher commercial value compared to those obtained through VOS, such as methanol and ethanol. This outcome can be attributed to three principal reasons. Firstly, natural compounds obtained through VOS may contain the solvent residues in the final product, limiting the extract application. Recent discussions have revealed that supplementing carotenoids (hydrophobic pigments) obtained through VOSs resulted in inflammatory responses in Wistar rats, particularly affecting both liver and kidney pro-oxidative pathways [27,28]. This adverse effect was not observed when the rats were supplemented with extracts obtained with alternative solvents, like eutectic solvents. Secondly, pigments extracted through VOS exhibit poor shelf-life [29–31], thereby impairing their technological performance. When subjected to continuous mild heat (55 °C), the anthocyanins extracted from grape pomace using VOS displayed a half-life time at least four times shorter than those obtained using eutectic solvent as a solvent [21]. Additionally, when the anthocyanins extracted from eutectic solvent were loaded into SiO_2 adsorbent material (as depicted in Scenario II), which serves as an alternative carrier agent, the shelf-life increased by six times [21]. These findings demonstrate that, in this case, an alternative approach offered a win–win situation by simultaneously mitigating energy and cost

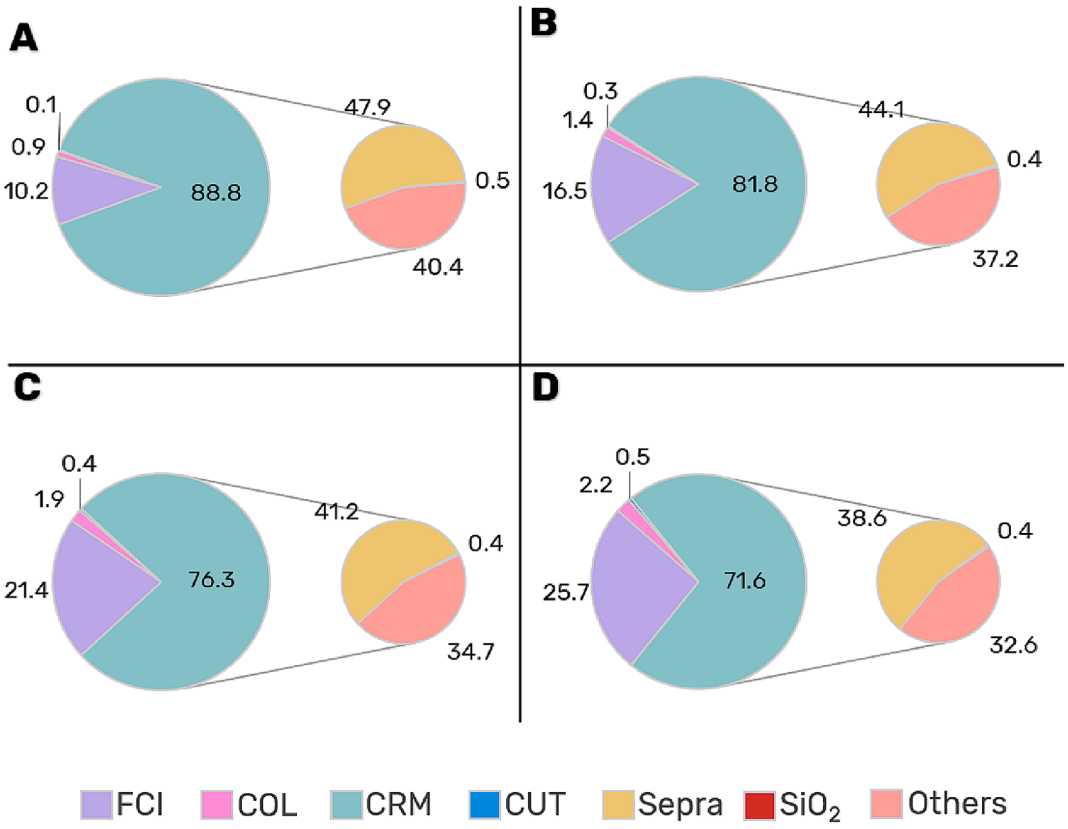

Fig. 6. Effect of the number of reuse steps in the SPE on cost of manufacturing (COM) composition simulated for Scenario II: (a) seven reuses; (b) five reuses; (c) three reuses; and (d) one reuse step. Pie chart on the left is composed of fixed capital of investment (FCI), cost of operational labor (COL), cost of raw material (CRM), and cost of utilities (CUT). The pie chart on the right comprises Sepra $C_{18}E$, SiO2, and other components representing the costs of raw materials (CRM).

requirements, resulting in a possible higher value-added product with lower expenditure. Thirdly, the eutectic mixture containing nicotinamide holds potential as an active ingredient in various formulations, particularly in the cosmetic sector. Nicotinamide, also known as vitamin B3, is frequently utilized in facial creams and other skincare formulations due to its significant role in combating skin conditions such as acne [32]. Therefore, based on these factors, it can be concluded that the selling price of anthocyanins obtained through eutectic solvent-mediated extractions should be higher than those obtained using VOS, which alleviates the initial costs of the industrial platform guided by the circular economy and green credentials.

Fig. 4 shows the composition of the costs of manufacturing for the three scenarios. Regardless of the Scenario, the main components were the cost of raw materials and fixed capital of investment. The cost of raw materials is the most relevant condition due to the need to acquire several raw materials for production (different solvents and Sepra $C_{18}E$ adsorbent material). On the other hand, fixed capital of investment is usually a relevant component in the costs of manufacturing in extraction industrial plants [33–39], because high-cost equipment and facilities are needed, often made of expensive materials such as stainless steel. On the other hand, the cost of operational labor and the cost of utilities had low impacts on the manufacturing costs, with percentages below 3.6%. Fig. 6 also shows how Sepra $C_{18}E$ and SiO_2 impact the cost of raw material. For example, in Scenario I, the cost of raw materials is practically the cost of acquiring solvents and grape pomace; in Scenarios II and III, it is noted that, although these two processes reuse the Sepra $C_{18}E$ eight times, its acquisition impacts the cost of raw material by approximately 50%.

With these findings, the importance of reusing and the need to investigate new adsorbents becomes evident, considering their performance in separating the target molecules, their regeneration capacity, and production cost. Furthermore, these data emphasize the importance of exploring new adsorbent materials, especially biobased ones, capable of achieving comparable performance to chromatographic adsorbent materials at a reduced cost. One promising avenue worth consideration is the use of biochar materials. Biochar has already demonstrated its effectiveness in remediating various environmentally harmful compounds, including synthetic dyes [36], metals [37], and pesticides [38]. Therefore, investigating the potential of biochar as an alternative adsorbent material shows great promise and could contribute to more cost-effective solutions in various applications.

3.1.2. Effect of using the adsorbent material (Sepra C_{18E})

As discussed in the previous section, Sepra $C_{18}E$ adsorbent material is critical in producing anthocyanin extract but significantly impacts manufacturing costs. In this section, we focused on investigating the effect of the number of reuses on the response variables of the cost simulation for Scenario II. Fig. 5 shows how the reused steps affect the costs of manufacturing, productivity, and the number of batches. Both the costs of manufacturing and the number of batches exhibited an exponential decrease (Fig. 5A and B). At the same time, the annual productivity increased (Fig. 5A) with the increase in the number of times Sepra $C_{18}E$ is reused. The decrease in the number of batches is attributed to the fact that each time Sepra $C_{18}E$ is reused, a fresh load of grape pomace is introduced to the five extractors. Therefore, one reuse step represents a new grape pomace load without replacing the SPE adsorbent. Likewise, eight loads of grape pomace can be processed with eight reuses without exchanging Sepra $C_{18}E$. The increase in reuses leads to time savings during the loading and unloading of Sepra $C_{18}E$ in the SPE vessels, consequently boosting productivity. Because of this enhanced annual productivity, there is a reduction in the costs of manufacturing. Furthermore, the recycling process needs a smaller volume of Sepra $C_{18}E$

to be purchased, as it can be reused up to eight times, resulting in cost savings.

To further observe the impact of different reusing steps on the cost-effectiveness of the process, Fig. 6A (seven reuses), 6B (five reuses), 6C (three reuses), and 6D (one reuse) are provided. The impact of Sepra $C_{18}E$ on the cost of raw materials remains consistent across all scenarios (pie charts on the right). Furthermore, and as expected, an increase in the number of reusing steps has a notable impact on the percentage of the cost of raw materials and fixed capital investment. The increase in the number of reusing steps decreased the relative contribution of the cost of raw materials to the overall manufacturing costs due to the smaller amount of Sepra C_{18E} required. Consequently, as the cost of raw materials decreases, other components, such as the cost of utilities and operational labor, experience a slight increase. Nevertheless, it was worth noticing that the reduction in the cost of raw materials from eight to one reuse step leads to a considerable increase in the fixed capital of investment, rising from 10.2% (Fig. 6A) to 16.5% (Fig. 6B).

3.1.3. Impact of selling price on payback time

The products from the three different processes simulated in this work are extract I from Scenario I (anthocyanin-eutectic solvent-extract loaded into SiO_2); extract II from Scenario II (anthocyanin-water-extract loaded into SiO_2), and extract III from Scenario III (dried anthocyanin extract in freeze drying device). To the best of our knowledge, no products with characteristics similar to those of the three extracts available on the market exist. Therefore, indicating a sales price based on prevailing market practices is not trivial. To address this challenge, we propose an inverse analysis in this section; that is, given certain payback times based on a project's lifetime of 15 years, we estimate the selling price that should be applied, and the results are presented in Table 1.

The first observation from Table 1 is that, regardless of payback time, there is a significant difference in the selling price scenarios. This difference is comprehensible because the products exhibit distinct global annual production amounts, composition, and, consequently, different anthocyanin concentrations. In increasing order of purity, we have the extract from scenarios I, II, and III, which clearly reflects the selling price, increase in that order. The second observation pertains, as expected, to the decrease in the selling price with an increase in the payback time for each Scenario. Notably, regardless of the Scenario, the selling price considerably decreases up to 10 years and then experiences a slight diminishing. Therefore, based on the provided information, investors may gain perspective on the relationship between selling price and payback time for the three scenarios simulated in this work. Moreover, the price discrepancies observed between scenarios II and III result from the extensive scale and prolonged usage of freeze-drying methods, significantly elevating the final selling price. In this context, adopting the SiO_2-based strategy for drying anthocyanin extracts is a highly relevant approach that can be easily replicated for various extract types. Additionally, our previously published article conducted a life cycle assessment of these three distinct scenarios, revealing the substantial environmental impact associated with the process outlined in Scenario III. Therefore, opting for SiO_2 instead of conventional freeze-drying technology represents a prudent strategy that not only mitigates the environmental footprint but also enhances overall profitability.

4. Conclusions

The simulated Scenarios presented in this study reveal that attaining economic viability through raw material reusability increases initial costs when establishing a sustainable factory. However, given the challenges posed by the sustainable development goals, overcoming these obstacles becomes imperative. Encouragingly, considerable progress has already been made, including developing alternative processes for recovering natural pigments with superior technological performance and maintaining the use of solvents. Considering the significance of nicotinamide as a vital active ingredient with proven benefits in treating dermal diseases, the obtained extract holds a higher value than traditional solvents and can be a wise strategy to be tested in other extraction platforms. Nonetheless, achieving this value demands a higher initial manufacturing cost and additional investments to facilitate solvent reuse. This offers a considerable advantage, as it can potentially elevate the final extract's selling price and alleviate the manufacturing costs. Our findings have emphasized the importance of exploring inexpensive adsorbent materials seamlessly integrated with chromatographic adsorbents, thereby reducing the overall costs of the developed circular process. We have created a compelling proposition for reusing the adsorbent Sepra C18E based on our current results, demonstrating clear financial advantages. By capitalizing on these advancements and the commercial value of the extract, it becomes feasible to navigate the economic landscape while simultaneously addressing the sustainable development goals.

Moreover, it is emphasized that adopting a SiO_2-based drying strategy offers a practical alternative to the conventional freeze-drying approach. Given the existing literature on various extraction platforms utilizing alternative solvents like eutectic solvents, this study stands out as a pioneer in illustrating a financially viable scenario for employing eutectic solvents in large-scale processes. It not only opens prospects for future research, particularly in streamlining investments in extract purification, but also encourages the production of ready-to-use extracts with higher value-added potential compared to those obtained with volatile organic solvents (VOS). Additionally, it reduces the need for substantial initial investments in purification strategies.

Table 1
Effect of the selling price on the payback time for the extracts obtained from processes simulated in scenarios I, II, and III.

Payback time (Year)*	2.5	5	10	15
Scenario I (US$)	75.0	64.0	56.0	54.5
Scenario II (US$)	109.0	97.0	91.4	89.5
Scenario III (US$)	217000.0	190000.0	176000.0	172500.0

* The payback time was determined in relation to the monetary value (in US dollars) associated with the commercialization of extracts derived from the three distinct Scenarios. These scenarios were assessed based on the yield ($mg_{anthocyanins}.g^{-1}_{grape\ pomace}$).

CRediT authorship contribution statement

Leonardo M. de Souza Mesquita: . **Juliane Viganó:** Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Priscilla Veggi:** Methodology, Investigation, Formal analysis, Data curation. **Letícia S. Contieri:** Investigation, Formal analysis, Data curation. **Filipe H.B. Sosa:** Methodology, Investigation, Data curation. **Veridiana Vera de Rosso:** Supervision, Funding acquisition. **Sónia P.M. Ventura:** Writing – original draft, Supervision, Funding acquisition. **Maurício A. Rostagno:** Writing – original draft, Supervision, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.seppur.2024.127647.

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