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Performance of small-scale composting in low ambient temperatures: Effects of adding animal by-products and recycling leachates

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ABSTRACT

Decentralized composting is an emerging method for managing biowaste, engaging waste generators as active recyclers in the waste management cycle. Evaluating performance and identifying optimization opportunities within this composting framework is essential to maximize its benefits and address its challenges. In small-scale composters, fresh waste is continuously mixed with previously added materials, shifting the typical composting process. As with larger systems, the composition of the feedstock influences the temperature profile and the quality of the final product. The issue of whether to include animal-source waste remains controversial in the development of standards and program guidelines. On the other hand, evaluating a leachate recycling method could help prevent nutrient loss and mitigate environmental impacts when bulking agents are lacking. In this study, kitchen and garden wastes were composted in 500-L static composters under cold climate conditions. We examined obtained compost stability, maturity, and quality parameters to determine the effects of adding animal by-product waste and/or recycling leachate. Our findings indicate that including animal by-products allows reaching sanitation temperatures under cold weather conditions and that recycling leachates could reduce nutrient losses and alleviate environmental and other user concerns while improving temperature, stability, maturity, and product quality patterns in decentralized composting.

Introduction

Decentralized composting is a highly effective method for treating the biodegradable portion of municipal solid waste. Recognized as one of the best available practices, it significantly improves municipal solid waste management by reducing waste transportation, treatment costs, and the volume of waste sent to landfills, as evidenced by numerous studies (Lleó et al., 2013; Pai et al., 2019). This cost-efficient technology has been successfully applied to kitchen and garden waste treatment in various settings, including institutions, neighborhoods, and homes (Platt et al., 2014; Vázquez et al., 2020). Household and community composting offers a viable technological solution for managing organic waste across different socio-economic contexts. Moreover, small-scale composting innovatively engages waste generators as key participants in the waste treatment process, enhancing community environmental awareness and commitment (Adhikari et al., 2010; Faverial and Sierra, 2014).

Recent strategies within the Circular Economy framework, such as

Abbreviations: C:N ratio, Carbon to nitrogen ratio; CCQC, California Compost Quality Council; DH, Dehydrogenase enzyme activity; GI, Germination index; HR, Humidification ratio; HI, Humidification index; LSD, Least Significant Difference; LRFV, Leafover raw fruits and vegetables; m.a.s.L., Meters above the sea level; NTD, Number of thermophilic days; OM, Organic matter; PFRPs, Process to Further Reduce Pathogens; Pha, Percentage of humic acid; PI, Polymerization index; RG, Relative germination; RRG, Relative root growth; T-MV, Treatment including animal by-products and vegetable waste, without leachate recycling.; T-MVL, Treatment including animal by-products and vegetal waste, with leachate recycling; T-V, Treatment including vegetable waste, without animal by-products or leachate recycling.; THS, Thermophilic heat sum; TKN, Total Kjeldahl nitrogen; TOC, Total organic carbon; WSC, Water soluble carbon.

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the United States National Strategy for Reducing Food Loss and Waste and Recycling Organics (USEPA, 2024), the National Strategy for Organic Wastes, from Chile (2021), and the Spanish Act 7/2022, of waste and contaminated soil for a circular economy (2022), showed a strong commitment to combining centralized and decentralized composting systems. This scenario requires further discussion and specifications for the small-scale processes to be as safe and effective as the centralized ones (Vázquez et al., 2020).

Small-scale composting often struggles to achieve thermophilic temperatures, the predominant way to sanitize composting materials, beyond others like biological antagonism or competition for energy (Vinnerås et al., 2010; IRAM, 2011). This issue can lead to skepticism among technicians, public officials, and household users who wish to advocate for decentralized composting systems, especially in challenging weather conditions (Barrena et al., 2014; Storino et al., 2016a).

Temperature plays a crucial role in sanitizing compost by destroying pathogenic microorganisms, minimizing vector attraction, reducing unpleasant odors, and preventing the viability of weed seeds (Onwosi et al., 2017; Stehouwer et al., 2022). According to the Argentinian standard IRAM-29556-1 (2011) and the United States standard called "Process to Further Reduce Pathogens" (PFRPs) (USEPA, 2003), an effective compost sanitization in closed containers or in-vessel composting requires maintaining a temperature above 55 °C throughout the composting mixture for at least three consecutive days. Even though those parameters are frequently used as references, they were not specifically developed for small-scale systems, and their application should be further discussed in such systems (Arrigoni et al., 2015; Storino et al., 2018).

In commercial compost bins, typically 40 to 500 L in volume, the thermal inertia is lower than that of larger systems. Consequently, the rate of metabolic heat generated is often insufficient to offset the heat loss to the surrounding environment, making it challenging to achieve and maintain the cited temperatures required for sanitization. While small-scale composting systems may struggle to meet PFRPs or other temperature-based sanitization standards, many studies (Abdullah et al., 2013; Benjawan et al., 2015; Sánchez et al., 2015) have demonstrated good temperature performance in tropical and favorable climatic conditions or controlled laboratory environments (Barrena et al., 2014; Faverial and Sierra, 2014; Varma and Kalamdhad, 2014). However, in cold climates, such as the Andean Patagonia region in Argentina, the typically low ambient temperatures can maximize heat loss and restrict microbial activity, hindering compost stabilization and sanitization and extending the time required for compost maturation.

Unlike full-scale composting systems, where the process begins once the pile or windrow is built and ends when all materials have matured, small-scale composting involves frequent additions of fresh waste. This practice alters the expected process evolution due to the mixing of materials at different stages of decomposition; for instance, in a previous study (Arrigoni et al., 2018), a "stratification" effect was observed in vertical static-compost bins, with more pronounced unwanted effects for the process at the bottom than at the top of the composting device, likely due to leachate movement from the upper to lower layers. This stratification can extend the maturation period (Barrena and Sánchez, 2022; Sánchez, 2022), which requires further investigation for this technology performance improvements (Cheng et al., 2022).

On the other hand, decentralized composting methods often recommend avoiding animal-origin wastes to mitigate their lower degradability and higher risk of disseminating pathogens or pest attraction. However, Storino et al. (2016b) found that adding raw animal by-products could accelerate compost maturation and increase nutrient content in the final product. The impact of animal by-products (raw or cooked) as feedstock on the whole process performance remains debated in household and community composting programs. Another aspect affecting this technology's performance concerns the biowaste-to-bulking agent ratio (Alves et al., 2023; Rao and Parsai, 2023), which, in many cases, requires managing leachates. Reintroducing leachates to the process might increase anaerobic zones, leading to unwanted odors, vector attraction, and other undesirable conditions. However, it also has the potential to recycle valuable nutrients and mitigate environmental impacts on the surrounding area (Roy et al., 2018).

Thus, studying the incorporation of animal by-products as feedstock and recycling leachate could enhance small-scale composting systems regarding temperature performance and nutrient recovery, resulting in particular benefits in cold weather applications (Barrena and Sánchez, 2022). This work aims to evaluate the performance of a small-scale composting system in cold-weather conditions when introducing animal by-product waste and recycling the generated leachates. The evaluation includes temperature performance, biological activity, and easily degradable carbon as stability parameters, as well as maturity and quality parameters, which determine the potential uses of the compost produced (CCQC, 2001; IRAM-29556-1, 2011; Mazzarino et al., 2012; Mahapatra et al., 2022).

Materials and methods

Composting devices and experimental design

Composting devices were fabricated using recycled plastic tables arranged in a cylindrical shape, featuring a plastic base to support composting materials and a circular lid to shield against rainwater, snow, animals, and pests (Fig. 1a). The plastic base facilitated leachate drainage for recycling through a perforated plastic plate with 20 holes, each 2 cm in diameter (Fig. 1b). A 1.5 L plastic bottle connected to the base served for leachate collection (Fig. 1c). Additionally, two "perimeter doors" were installed for compost harvest. The composter's overall dimensions were: i) total height: 120 cm (effective operational height: 100 cm); ii) inner diameter: 80 cm; iii) practical volume for waste treatment: 500 L.

A small-scale composting experiment using the above-described devices was conducted outdoors in San Carlos de Bariloche (41° 07′S; 71°19′O), a mountain city in North West Patagonia, Argentina, at approximately 890 m.a.s.L. The climate in this region is cold-temperate, with dry summers and an average annual temperature of 8.4 °C. The total rainfall is approximately 1000 mm annually, usually in autumn and winter.

Pre- and post-consumer kitchen wastes served as the primary feedstock for the composting process. The kitchen waste was originated by an institutional catering service responsible for approximately 500 daily meals. Additionally, small amounts of garden waste (grass clippings) were occasionally added to the composting materials. Pine wood shavings were employed as a bulking agent. The size of the bulking agent particles varies from 1 to 3 cm in diameter. Animal by-products included cooked or uncooked meat, dairy, and fats.

The experimental design included three treatments: i) T-MV, Treatment incorporating animal by-products and vegetal waste without leachate recycling; ii) T-MVL, Treatment incorporating animal by-products and vegetal by-products, with leachate recycling; and iii) T-V, Treatment solely incorporating vegetable waste, without animal by-products or leachate recycling. Each treatment comprised three replicates, totaling nine 500 L-composting devices used in the trial. In all treatments, the ratio of kitchen waste (with or without animal by-products) to the bulking agent (pine wood shavings) was 3:2 based on volume. Composters were fed thrice a week for 52 days until each composter was fulfilled. Feedstocks were cut into 5 cm long/wide pieces before being added to the composters. After each addition, materials were manually mixed. When added to each composter, kitchen waste and bulking agent batches were equally divided and measured in 10-liter fractions. Treatment means additions accounted for T-MV: 338 ± 4 kg (1050 ± 9 L); T-MVL: 337 ± 7 kg (1106 ± 11 L) and T-V: 289 kg (1093 ± 11 L). The average weight proportion of kitchen waste-grass clippings-wood chips in the mixtures was: T-MV: 73–4-23 %, T-MVL: 73–5-22 %, and T-V: 57–5-38 %. Moisture content was regularly

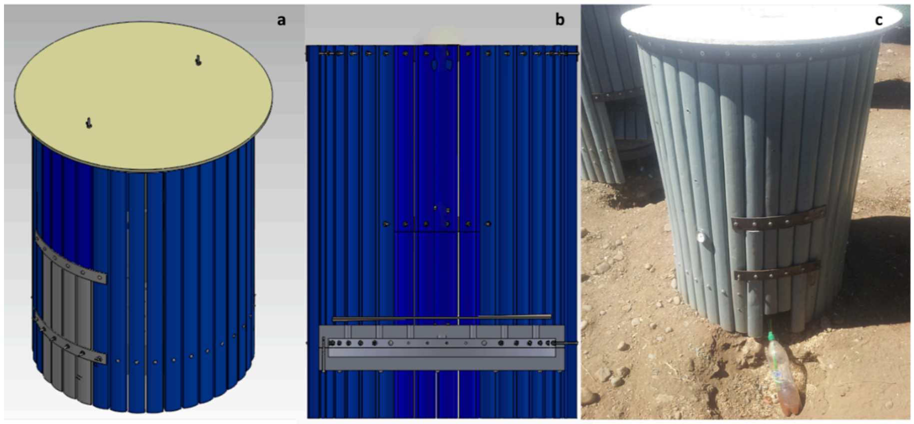

Fig. 1. Static composter of 500 L made with plastic, including two lateral doors and a circular lid in Fig. 1a. A perforated plastic base with 20 holes of 2 cm diameter used to drain leachate to be recycled shown as the grey component in Fig. 1.b., and a plastic bottle of 1,5 L connected to the plastic base for leachate collection as seen in Fig. 1.c.

monitored in the field using the "fist test" (Storino et al., 2018). The leachate was collected up to two times a week and distributed in similar proportion to each composter (T-MVL). No extra irrigation was applied to any treatment.

Temperature monitoring and sampling

For temperature monitoring, eight holes were perforated every 10 cm from the bottom of the composting device up to 80 cm height (Fig. 1c). A stainless steel analog composting thermometer was used to measure temperatures every two days through the perforated holes at depths of 15 and 40 cm from the external perimeter of the composter. The temperature was measured from the first waste addition until the process stabilized at ambient temperature levels. Daily mean ambient temperature data were automatically recorded by a Davis Vantage Pro2 weather station.

Samples of the composting mixture for process performance evaluation were collected from all composters at 103, 161, 203, and 244 days from the initial incorporation of organic waste, corresponding to 51, 109, 151, and 192 days from the last waste addition. Each composite sample, with an approximate weight of 350 g, consisted of six subsamples from each composter taken with an *Edelman-type* auger from approximately 30 cm above the bottom layer, following experiences from previous studies (Arrigoni et al., 2018). Final compost quality and maturity analyses were conducted on samples taken 336 days after the initial biowaste incorporation once all the material from each composter was thoroughly homogenized. When sampling for stability parameters, a portion of the fresh sample was set aside and stored at 4 °C to measure CO_2 evolution, while the remaining portions were air-dried and ground for chemical analyses.

Samples analyses

The performance of the process was assessed through the determination of carbon dioxide (CO_2) release, water-soluble carbon (WSC), and the WSC: total Kjeldahl nitrogen (TKN) ratio as material stability parameters. Germination index (GI), Dehydrogenase enzyme activity (DH), concentration of ammonium, and the NH_4^+:NO_3^- (ammonium/nitrates) ratio were evaluated as compost maturity parameters (CCQC, 2001; IRAM-29556-1, 2011; Mazzarino et al., 2012). Final compost quality from the different treatments was also examined through final pH and electrical conductivity values, nutrient contents (Extractable-P, Ca, Mg, K, and Na), and the characterization of humic substances. (Mazzarino et al., 2012; Mahapatra et al., 2022).

Stability and maturity parameters

Biological activity was assessed by measuring the respiration rate under controlled incubation conditions, indicated by CO_2 evolution. The sample is incubated, and the released CO_2 is absorbed in a NaOH solution trap. Evolved CO_2 is indirectly measured by quantifying the formed carbonates through excedent alkaline solution titration with HCl (Jäggi 1976, as cited in Alef, 1995). Briefly, perforated 50 ml plastic centrifuge tubes with 15–20 g of fresh sample (in triplicate) were placed in 250 ml flasks containing 10 ml of 0.5 N NaOH solution. These flasks were sealed and incubated at 25 °C for 72 h. Controls consisting of three flasks containing only the alkaline trap solution (NaOH solution) were included. Any sodium carbonates formed after 24 h of incubation were precipitated using 1–2 ml of a 3 N $BaCl_2$ solution. The excess NaOH was then titrated with 0.25 N HCl. This process was repeated at 48 and 72 h of incubation after replenishing the alkaline trap solution. The CO_2 production rate (mg CO_2 kg^{-1} dry matter h^{-1}) was calculated based on the average CO_2 production during the final two days of incubation (Tognetti et al., 2007).

Water Soluble Carbon (WSC) content was determined in aqueous extracts obtained from triplicate samples (1:10 ratio: 4 g dry sample/40 ml distilled water) after agitation for 2 h, followed by filtration through Whatman filter paper No. 42. WSC was quantified as chemical oxygen demand (COD) through acid digestion of an aliquote of the sample aqueous extract with a sulfuric chromic mixture ($K_2Cr_2O_7/H_2SO_4$) at 150 °C for 2 h. Dichromate reduction was analyzed by spectrophotometry at 600 nm and quantified by comparison with potassium biphthalate standards of known concentration (APHA, 1998). Total organic carbon (TOC) was calculated based on the organic matter (OM) content determined gravimetrically through sample ashing at 550 °C. The carbon fraction was estimated as TOC using the equation $TOC = OM \div 1.8$ (Navarro et al., 1990). The Total Kjledhal Nitrogen (TKN) was measured using the semi-micro Kjeldahl method (Tognetti et al., 2007).

The germination index (GI) utilized to assess phytotoxic effects was determined following the method outlined by Zucconi et al. (1981). This index is based on the relative germination (RG) and the relative root growth (RRG) of selected plant species seeds in compost-water extracts. Ryegrass (*Lolium multiflorum*) and radish (*Raphanus sativus*) were indicators for acute phytotoxicity. Twenty seeds of each plant species were evenly distributed onto filter paper sheets in Petri dishes. Four plates were prepared per compost sample, and corresponding germination controls were prepared with distilled water. 3 ml of the sample extract (1:10 ratio air-dried compost: distilled water; 1 h shaking and centrifugation) were added to the plates. The plates were incubated in darkness at 25 ± 1 °C for seven days. Following the incubation period, the number of germinated seeds (radicle length > 5 mm) and the length of developed roots were recorded to determine the GI value according to the following equation: GI=RG * RRG; where RG is the average of germinated seeds in the extract divided by the average number of germinated seeds in distilled water (control) in percentage and RRG is the average root length in the extract divided by the average root length in distilled water in (%).

The dehydrogenase enzyme activity (DH) is used as an indicator of microbial community activity to assess compost maturity (Tiquia, 2005). The evaluation of dehydrogenation enzymatic systems followed the method proposed by Tabatabai (1994, as cited in Tognetti et al., 2007) for soils and sediments. This involved incubating the sample with $CaCO_3$ and a 3 % w/v solution of TTC (2,3,5-triphenyl tetrazolium chloride) in darkness at 37 °C for 24 h. The enzymatic dehydrogenation system in the sample reduced the substrate to TPF (2,3,5-triphenyl formazan). After incubation, the TPF was extracted with methanol, and its concentration was determined spectrophotometrically at 485 nm. Results are expressed as μg TPF per gram of dry sample.

The ammonium concentration was quantified using the Berthelot reaction, while NO_3^- was measured via coppered Cd reduction. NH_4^+ and NO_3^- were extracted using 2 M KCl solution at a ratio of 1:10 (air-dried compost sample) (Tognetti et al., 2011).

Final compost characterization and quality

pH and electrical conductivity were assessed in aqueous extracts of air-dried samples at a ratio of 1:10, obtained following 2 h of stirring and subsequent filtration using Whatman No 42 filter paper. Extractable phosphorus levels were determined after sample extraction in 0.5 M $NaHCO_3$ at a ratio of 1:100 using the molybdate-ascorbic acid method (Tognetti et al., 2011). The total nutrient contents (P, Ca, Mg, K, and Na) were analyzed in the calcination ashes (obtained at 550 °C) analysis. Extraction was done using HCl, followed by atomic absorption spectroscopy determination (Tognetti et al., 2011).

Humic substances (HS=C_{EX}: alkali-extractable organic-C) were extracted using 0.1 M NaOH solution at a ratio of 1:10 (air-dried compost: solution) with agitation for 4 h under a nitrogen atmosphere. The extracts were then centrifuged at 2500 rpm for 15 min, and the retained extracts were filtered. A 4 ml aliquot of the extract was combined with 4 ml of concentrated sulfuric acid and 98 mg of potassium dichromate. The sample was digested at 150 °C for 15 min, followed by a resting period of approximately 10 h. After adding 2 ml of deionized water and stirring, the transmittance (%T) of the solution was measured at a wavelength of 590 nm using a glucose standard curve for quantification.

Humic acids (HA=C_{HA}: humic acid-like organic-C) and fulvic acids (FA=C_{FA}: fulvic acid-like organic-C) were determined from the alkaline extract under acidic conditions (pH=2). The precipitate was obtained by centrifugation at 4000 rpm for 15 min. The carbon in the precipitate represented the fraction of HA in the HS, while the non-precipitated carbon indicated the fulvic acid-like fraction of the C_{EX}. These fractions were determined by spectrometry as described for humic substances (Sims and Haby, 1971, cited in Campitelli et al., 2006). HA was determined by the difference between the carbon content of the HS and the carbon content of the FA in the precipitate.

Obtained values were used to calculate the following maturity indicators: Humidification ratio (HR): C_{EX} /TOC x 100, showing the synthesis of recalcitrant compounds contrasted to TOC; Percentage of humic acid (Pha): C_{HA}/C_{EX} x 100; Humidification index (HI): C_{HA}/TOC andPolymerization index (PI): C_{HA} /C_{FA}. HI and PI indexes are related to the formation of complex molecules using simpler ones, to the decrease of non-humic-like substances, and their correlation with maturity parameters.

Statistical analysis

Significant differences in stability, maturity, and compost quality parameters between the treatments were analyzed using General Linear Models (GLM) of mixed effects. Post-hoc comparisons between means were made by Fisher's LSD test, with a confidence limit ≥ 95 %. All analyses were performed with INFOSTAT v. 2015 software (Di Rienzo et al., 2011).

Results and discussion

loss and leachate generation rates

The average fresh weight of the compost produced was 138 (±5) kg for the treatment with animal by-products and vegetables (T-MV), 108 (±6) kg for the treatment with leachates recirculation (T-MVL), and 101 (±5) kg for the treatment with vegetable waste only (T-V). These values correspond to 41 % (TMV), 32 % (T-MVL), and 35 % (T-V) of the average initial feedstock mass introduced into the composters, indicating an approximate reduction of 59 – 68 % of the starting material lost through oxidation and mineralization into vapors or leachates. If the weight of the bulking agent is excluded, then approximately 80 – 88 % of the original kitchen waste and grass clippings mass will be lost during the composting process. These values align with those reported by Storino et al. (2016 a,b), Guidoni et al. (2018), Sakarika et al. (2019), and Bhave and Kulkarni (2019), which range from 47 – 70 % in weight loss and 30 – 92 % for volume reduction of the composting mixture.

Approximately 18 L of leachate were recycled into each composter in the T-MVL treatment, adjusting a generation rate of 53 L per ton of composting materials or 16 L per 1000 L of composting materials, which is comparable to the following rates reported by Roy et al. (2018): 75–100 L per ton of mixed municipal waste; 5–50 L per ton for green waste; and 100 L per ton for sewage sludge composting. Guidoni et al. (2018) observed leachate generation rates ranging from 0 L per cubic meter to 87 L per cubic meter when composting leftover raw fruits and vegetables (LRFV) mixed with rice husk as a bulking agent, altering the LRFV: husk ratio from 70:30 % to 30:70 % in 40-liter reactors. This study highlighted the significant impact of the bulking agent ratio on leachate generation rates. Unlike the findings of Storino et al. (2016a), we did not require additional watering during the experiment. It is also noteworthy that the actual volume of produced leachate might exceed the total recycled leachate due to potential losses through the composter tables.

Composting temperature evolution

Temperature serves as a primary parameter for characterizing composting and frequently enables the assessment of various factors influencing the processes. While some authors have noted variable performance in achieving thermophilic temperatures (Storino et al., 2016b; Alves et al., 2023), others have observed poorer outcomes in thermophilic temperature development (Barrena et al., 2014; Abdullah et al., 2013; Vázquez and Soto, 2017; Bhave and Kulkarni, 2019).

Fig. 2 depicts the temperature profiles observed in our study. We noted a significant influence of incorporating animal by-product waste on thermophilic conditions, consistent with Storino et al. (2016b) findings. Treatments incorporating animal by-products (T-MV and T-MVL) exhibited superior performance compared to T-V, which solely included vegetable waste. However, no clear distinction was observed between T-MV and T-MVL, despite both incorporating the same type of waste, with the latter involving recycling-generated leachates.

Considering different composting highs, thermophilic temperatures (≥45 °C) were continuously developed during 50 days in treatments that included animal by-products. This outcome was closely linked to the waste incorporation phase. Conversely, in our study, T-V exhibited intermittent thermophilic temperature development during the incorporation period, aligning with previous findings (Storino et al., 2016a).

While the USEPA (2003) standard is commonly cited for assessing thermal performance in composting, it has been previously suggested that it might not be suitable for confirming the sanitization of composting materials (Arrigoni et al., 2018). This is because there is typically significant variability within the composting mass concerning

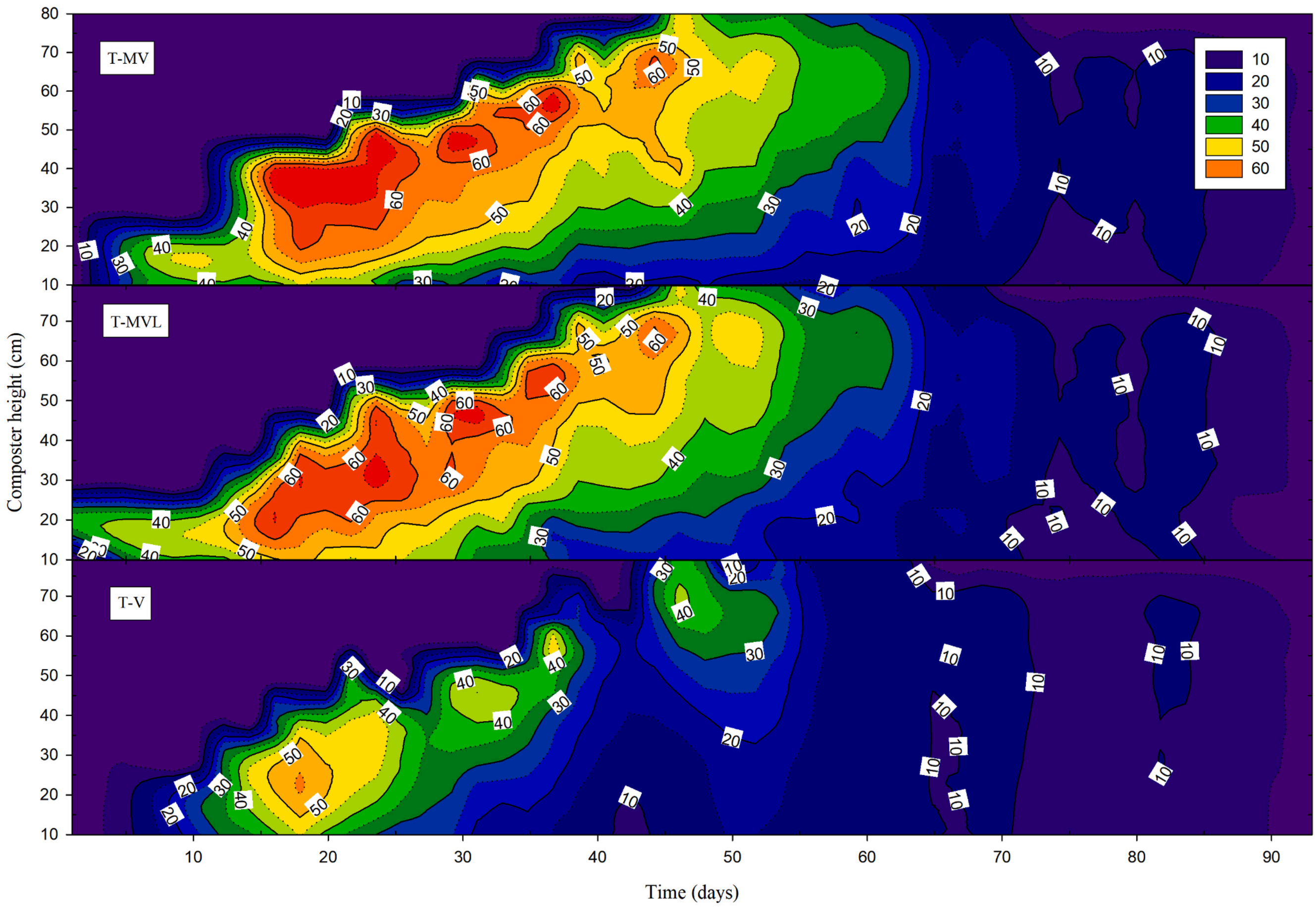

Fig. 2. Composting evolution against time and the reactor height in therm of average temperatures of the three treatments projected in a 2 D-coloured contour plot. The isotherm represents temperature values (°C) in 5-degree ranges from 10 – 60 °C. Warm colors indicate the best thermal performance between 20 and 50 cm in the height of the composter prototype throughout the experiment. T-MV: Treatment including animal by-products and vegetable waste, without recycling leachates, T-MVL: Treatment including animal by-products and vegetable waste, with recycling leachates, T-V: Treatment including vegetable waste, without animal by-products or recycling leachates.

maximum and minimum temperatures and the absence of a mixing tool. However, despite the generally cold weather conditions, with an average temperature of 8.5 °C during the period, the inclusion of animal by-products waste enabled sanitization temperatures (USEPA, 2003) from day 17 to 47 (30 days), considering temperatures across the height of the composter in T-MV and T-MVL. In contrast, T-V only reached sanitization temperatures for 1 to 2 days (17 to 19), reflecting the closest performance to those reported by Margaritis et al. (2018) when looking to improve the composting of food waste (without animal by-product additions) through the addition of different minerals.

The feeding rate is rarely emphasized as a significant management practice in small-scale research (Abdullah et al., 2013; Storino et al., 2016a). Therefore, evaluating the generation rate as another factor influencing composting is essential. Storino et al. (2016a) suggested that the feeding rate could impact temperature evolution in small-scale composting systems, advocating for community composting over home composting due to larger loads promoting higher temperatures, thus aiding in the reduction of unwanted odors, seeds, and pathogens. While the present study did not test a specific hypothesis on this topic, our experience could be characterized as a community or institutional one, with a feeding rate of 6.5 kg day^{-1}, comparable to the waste generation of five to six families with three to four members, equating to 0.3 kg of biowaste per person per day.

Around 60 days into the composting process, there was a decline in temperatures, returning to ambient levels, potentially linked to the stabilization of the composting material (Sarika et al., 2014). As a proposal for current and future comparisons of temperature performance in small-scale composting systems, we computed two metrics: the number of thermophilic days (NTD), defined as the total days with temperatures exceeding 45 °C, and the thermophilic heat sum (THS), calculated as the cumulative difference between the daily compost temperature and 45 °C (Storino et al., 2016b) (Table 1).

The parameters statistically demonstrate the aforementioned effects among the three treatments, stating superior performance when animal by-products are included. This trend aligns with findings by Storino et al. (2016b), who observed comparable results in thermophilic days (NTD) for composting processes involving animal by-products, ranging from 10 to 45 days depending on the quantity of animal by-products and

Table 1
Temperature parameters by treatment for composting performance evaluation.

	T-MV	T-MVL	T-V	Ambient
Average temperature (°C)	33 ± 09 a	33 ± 0.9 a	22 ± 1b	8,5
Maximum temperature (°C)	67 ± 1 a	69 ± 1 a	57 ± 2b	11,6
NTD	19 ± 2 a	21 ± 1 a	3 ± 1b	
THS	157 ± 25 a	167 ± 5 a	5 ± 7b	

Mean values ± SD (n = 3). Different letters indicate significant differences ($p < 0.05$). T-MV: Treatment including animal by-products and vegetable waste, without recycling leachates, T-MVL: Treatment including animal by-products and vegetable waste, with recycling leachates, T-V: Treatment including vegetable waste, without animal by-products or recycling leachates. NTD: Number of thermophilic days (T>45 °C); THS: Thermophilic heat sum =Σday (T-45 °C).

bulking agent utilized, compared to less than one day when composting solely vegetable wastes. Similarly, the thermophilic heat sum (THS) exhibited similar outcomes for vegetable-only composting (=3) but reached values of 67 and 191 with the inclusion of 6 and 18 kg of animal by-products waste (in a 320 L composter) and 350 when employing 18 kg of animal by-products along with doubling the volume of bulking agent (resulting in a final v/v waste agent ratio of 1:1.2).

Nonetheless, when temperatures were above 45 °C, adding animal by-products temporarily promoted unwanted odors. Animal by-product waste is associated with a high nitrogen (or protein) content, increasing the risk of attracting flies, rodents, and birds, which is not desired for a composting system. Furthermore, an excess of nitrogen compounds has also shown an unwanted impact on the phytotoxicity of the produced compost (McSweeney, 2019; Guidoni et al., 2021).

Stability and maturity indicators

Stability and maturity parameters provide insights into the progression and effectiveness of composting. They reflect a decrease in the easily degradable carbon fraction contained in the composting materials, as well as a decrease in the microbial activity responsible for the degradation (stability) or the absence of phytotoxic compounds and properties in the matured compost (CCQC, 2001; IRAM-29556-1, 2011; Mazzarino et al., 2012). In community composting, stability indicators like CO_2 release, WSC, WSC/TKN, and O_2 uptake rate may be linked to the composter's retention time and, thus, to the system's capacity (McSweeney, 2019; Vázquez et al., 2020).

During the sampling period, minimal variations in WSC were observed (Fig. 3a). The stability reference of 17 g kg^{-1} (Bernal et al., 2009) for the mentioned WSC was attained within 103 days (or 15 weeks) after the initial waste incorporation across all treatments. This stabilization performance can be compared to the 24 weeks required for stabilized compost in the study by Storino et al. (2016b) and the four months required by Vázquez et al. (2020) to get a *Rottegrade Class* of IV-V. Although treatments incorporating recycled leachates tended to exhibit higher values, this difference was not statistically significant ($p < 0.05$). These results underscore that compost stability is associated with, but not solely dependent on, thermophilic temperatures (Barrena et al., 2014; Sánchez et al., 2015).

A decline was noted in the CO_2 release indicator between the second and final sampling periods (Fig. 3b), resulting in statistical differences in the CO_2 release rate measured at 160 (week 23) and 240 (week 34) days since the initial waste incorporation ($p < 0.05$). However, significant variability was observed within each composting unit, and no differences between treatments were detected. The final values recorded were 193, 230, and 225 mg CO_2 kg^{-1}h^{-1} for T-MV, T-V, and T-MVL, respectively. While all final values were near the 200 mg CO_2 kg^{-1}h^{-1} threshold considered indicative of stable compost (Bernal et al., 2009), they nearly doubled the stability reference of 120 mg CO_2 kg^{-1}h^{-1} suggested by Hue and Liu (1995).

When examining the WSC:TKN ratio (Fig. 3c) as a stability indicator, we observed similar patterns of evolution as seen with WSC and CO_2 release: notable variability within the same treatments, no distinct trend in parameter evolution during the sampling period, and values nearing the recommended thresholds in the final analysis.

Significant differences ($p < 0.05$) between treatments were only observed at the final sampling time for the WSC:TKN ratio. T-MV exhibited a lower mean value than T-MVL, indicating that leachate recycling may elevate the value used as a stability indicator. Moreover, T-MV was the only treatment to achieve the proposed threshold of 0.7 for stabilized products (Hue and Liu, 1995; Laos et al., 2002; Mazzarino et al., 2012). The final means were 0.6, 0.9, and 1.1 for T-MV, T-V, and T-MVL, respectively. However, none of the treatments reached the 0.3 threshold suggested by García et al. (1991).

In a prior study (Arrigoni et al., 2018), we observed that the lower segment of the composting materials, spanning from 0 to 20 cm in height, contained a less stabilized compost fraction compared to the upper segment (from 20 to 80 cm high) of the composting mass. Samples from the 20 to 40 cm height from the bottom of the composter exhibited elevated values for the ratio, likely influenced by the migration and accumulation of leachate in a more densely packed zone of materials.

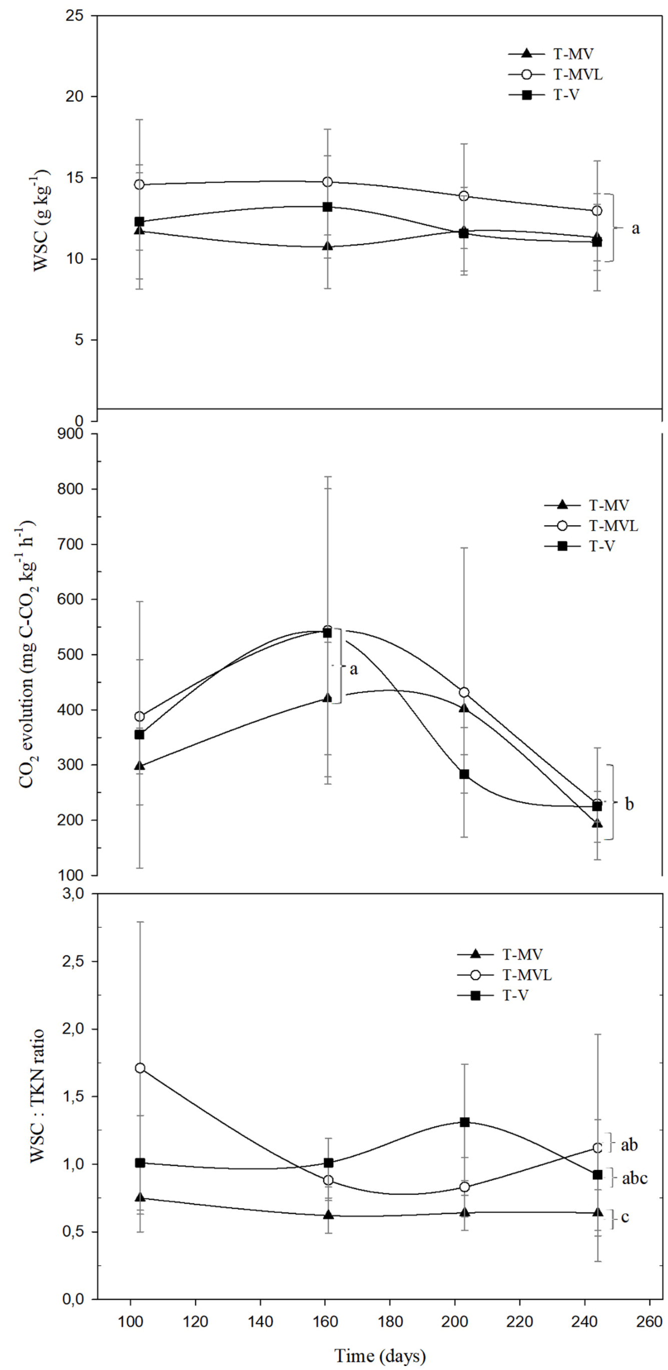

Fig. 3. Compost stabilization indicators: WSC – (water-soluble carbon), CO_2 evolution, and WSC:TKN ratio. Different letters indicate significant differences ($p < 0.05$) between treatments. T-MV: Treatment including animal by-products and vegetable waste, without recycling leachates, T-MVL: Treatment including animal by-products and vegetable waste, with recycling leachates, T-V: Treatment including vegetable waste, without animal by-products or recycling leachates.

We anticipate a clearer trend could emerge if we start measuring WSC and CO_2 evolution from the initial stages of the experiment (within the first 30 days of composting). However, in small-scale composting studies, this would involve sampling for stability analysis when the composter is not yet completely filled, and thermophilic temperatures are still developing. Additionally, we believe that the absence of mixing operations and the static nature of the chosen technology contribute to amplifying the observed effects. These observations underscore the absence of standardized procedures for performance evaluation in bin composting.

The composting process culminates with a product suitable for agronomic or environmental purposes. Mature compost should display a low biodegradation rate, with no harm to humans or animals, and should not exhibit any phytotoxic effects upon application (CCQC, 2001). Immature compost, on the other hand, is characterized by i) insufficient stabilization of organic matter, leading to a high oxygen demand that impacts root environments; ii) a scarcity of available nitrogen due to microbial demand; and iii) the presence of compounds detrimental to plant growth, such as phenolic compounds, ethylene, ammonia, and organic acids (De Campos et al., 2014).

All treatments achieved the target values in three of the six maturity assessment indicators: the Germinating Indexes (Rye Grass and Radish) and NH_4^+ (Table 2). Neither the elevated pH in T-V nor the increased electrical conductivity and nitrogen compounds resulting from the inclusion of animal by-products or leachate recycling had any adverse effects on these maturity parameters.

T-MVL consistently demonstrated a better performance across the remaining maturity indicators. Its lower dehydrogenase activity ($p < 0.05$) approached the recommended level (<35 µg TPF g^{-1}) for classifying compost as mature (Tiquia, 2005). Additionally, T-MVL was the sole treatment to achieve the suggested ratio of 0.3 for NH_4^+:NO_3^- (CCQC, 2001), although this was not significantly different from the other treatments. T-MVL and T-MV attained lower C:N ratios than T-V, which exceeded the target value for mature compost (Faverial and Sierra, 2014; Storino et al., 2016b). Furthermore, the absence of screening in the samples may have introduced woody pieces, thereby increasing the carbon source and variability within and between samples from the same composter and different treatments.

While the final values did not meet all the suggested maturity parameters for fully mature compost, the consistent values across sampling times indicate that the composts could be well-matured. These findings support the hypothesis that incorporating animal by-products in small-scale composting, along with recycling generated leachates, enhances the process and accelerates the maturation of compost.

Agronomic and quality parameters

Agronomic and quality parameters are crucial in determining suitable compost applications. Table 3 details the results for quality parameters in produced composts.When assessing the impact of animal-derived waste and leachate recycling, we observed that the final compost pH was influenced by the feedstock used, resulting in alkaline composts when only vegetable wastes were employed ($p < 0.05$). The pH of composts in treatments incorporating animal by-products remained within the optimal range of 6 to 7.8. In contrast, the pH of T-V composts was broader, typical of lower-quality composts (5 to 8.5) (CCQC, 2001). None of the treatments surpassed the threshold (pH<9) prescribed by guidelines for quality compost used in growing media (Wrap, 2011). However, previous small-scale composting investigations have documented elevated pH values when food waste served as the principal feedstock (Arrigoni et al., 2015).

The electrical conductivity increased with leachate recycling, showing significant differences between T-MV and T-MVL ($p < 0.05$), with T-V in between, with nonstatistical differences observed. None of the treatments exceeds the recommended agricultural threshold of 5 dS m^{-1} (CCQC, 2001). Nevertheless, dilution or additional control is advised for recycled leachates to prevent adverse effects when employing the final compost for vegetable growth.

Based on the organic matter predictions by Navarro et al. (1990) (OM~TOC * 1.8), all composts exhibited high OM content for soil amendment (>35 %), surpassing values from other small-scale studies (Faverial and Sierra, 2014; Barrena et al., 2014).

Both treatments that included animal by-product waste showed higher levels of TKN, NO_3^-, Ca, and P compared to compost made solely from vegetable waste ($p < 0.05$), affirming the impact of animal by-products on the final compost nutrient content (Storino et al., 2016b; Vázquez and Soto, 2017). Additionally, recycling leachate increased the Na content, making T-MVL the most influential treatment regarding the final nutrient content.

Contrary to Storino et al. (2016a), T-V exhibited higher K content compared to both animal by-product-inclusive treatments ($p < 0.05$), likely due to the higher presence of K in plant tissue. Except for K and total-P, the nutrient content was lower than that reported by other researchers (Varma et al., 2014; Ferial and Sierra, 2014), possibly due to the nutrient-rich cattle manure used by Varma et al. (2014) or a dilution effects from woody structuring materials in our work. The high organic matter content and C:N ratio observed in our final compost support this assumption.

The quality of organic matter, particularly its degree of humification, is closely linked to soil fertility. Thus, humic acid-like substances and their ratios are commonly used to evaluate compost quality and maturity (Campitelli et al., 2006). Although the reliability of humic-like substances as compost maturity indicators has been debated due to the co-extraction of non-humic substances with alkaline methods, most of the recommended parameters cited by Bernal et al. (2009) were met in all treatments (HR≥7.0; HI≥3.5; PHA≥50; and PI≥1.0). However, there were no significant differences between the treatments. Only the humification ratio (HR) showed higher values for T-MV than T-V, suggesting a potentially higher formation rate of humic acid-like substances in T-MV. To confirm this, it would be necessary to analyze the evolution of these parameters over time rather than just the final value.

Conclusions

Our experience demonstrated that small-scale composting under unfavorable cold weather conditions improved by adding animal by-product waste and recycling the leachate. Distinct performances during the active phase were observed, with animal-origin waste as the primary influencing factor. Leachate recycling or the inclusion of animal

Table 2
Maturity parameters used to compare composting in the cases with and without including animal by-products and recycled leachate.

Variable	T-MV			T-MVL			T-V		
Germination Index: Rye Grass (%)	100	± 16	a	82	± 16	a	83	± 16	a
Germination Index: Radish (%)	101	± 14	a	90	± 13	a	93	± 15	a
Dehidrogenase Activity (ug TPFg^{-1})	71	± 19	a	39	± 12	b	76	± 17	a
NH_4^+(g kg^{-1})	155	± 64	a	92	± 45	ab	37	± 5	b
NH_4^+:NO_3^- ratio	0,45	±0,22	a	0,11	±0,15	a	0,39	±0,36	a
C:N ratio	21	± 2	b	21	± 2	b	39	± 10	a

Different letters mean statistical differences ($p < 0,05$) between values from the different treatments. T-MV: Treatment including animal by-products and vegetable waste, without recycling leachates, T-MVL: Treatment including animal by-products and vegetable waste, with recycling leachates, T-V: Treatment including vegetable waste, without animal by-products or recycling leachates.

Table 3
Quality parameters used to compare compost quality for the feedstocks with and without animal by-products and recycled leachate.

Variable	T-MV			T-MVL			T-V		
pH (H_2O) 1:10	7,2	± 0,3	b	6,9	± 0,2	b	8,0	± 0,4	a
CE 1:10 (mS cm^{-1})	1,6	± 0,5	b	3,0	± 0,9	a	2,2	± 0,2	ab
TOC (g kg^{-1})	366	± 35	b	378	± 28	b	408	± 28	a
TKN (g kg^{-1})	17,2	± 1,1	a	17,6	± 1,6	a	10,4	± 2,0	b
Extractable-P (g kg^{-1})	0,604	± 111	b	0,695	± 167	ab	0,864	± 167	a
P (g kg^{-1})	3,7	± 0,3	ab	6,3	± 3,7	a	2,0	± 0,1	b
Ca (g kg^{-1})	35,3	± 1,5	a	39,0	± 8,6	a	15,1	± 0,7	b
K (g kg^{-1})	3,9	± 0,1	c	6,0	± 1,1	b	8,0	± 0,2	a
Mg (g kg^{-1})	2,1	± 0,1	a	2,1	± 0,1	a	1,9	± 0,1	a
Na (g kg^{-1})	1,6	± 0,1	b	2,6	± 0,1	a	1,6	± 0,1	b
C_{EX}	48,8	± 5,3	a	48,6	± 9,5	a	42,0	± 2,1	a
C_{HA}	23,7	± 2,8	a	25,1	± 7,2	a	23,9	± 3,3	a
C_{FA}	25,1	± 4,1	a	23,5	± 2,4	a	18,1	± 5,4	a
HR	13,4	± 1,4	a	12,8	± 2,3	ab	10,3	± 0,2	b
HI	6,5	± 0,7	a	6,6	± 1,8	a	5,9	± 1,0	a
P_{HA}	48,7	± 4,8	a	51,1	± 4,5	a	57,2	± 10,9	a
PI	0,96	± 0,19	a	1,06	± 0,20	a	1,45	± 0,68	a

Different letters mean statistical differences ($p < 0,05$) between values from the different treatments. C_{EX}: alkali-extractable organic-C; C_{HA}: acid-like organic-C; C_{FA}: fulvic acid-like organic-C; HR (humification ratio): C_{EX}/C_{org} x100; HI (humification index): C_{HA}/C_{org} x100; P_{HA} (percent of humic acids): C_{HA}/C_{EX} x100; PI: C_{HA}/C_{FA}. T-MV: Treatment including animal by-products and vegetable waste, without recycling leachates, T-MVL: Treatment including animal by-products and vegetable waste, with recycling leachates, T-V: Treatment including vegetable waste, without animal by-products or recycling leachates.

by-products did not adversely affect stability and maturity parameters; on the contrary, those treatments support the hypothesis of accelerating stabilization and maturation periods.

Uncontrolled bulking agent-to-biowaste ratio conditions or scarce availability of bulking agents may benefit from a leachate collection system that helps prevent nutrient loss and unwanted environmental impacts in the surrounding area without negatively affecting temperature performance or stabilization. Thus, incorporating animal-origin waste and recycling leachates in cold-weather small-scale composting systems can improve their temperature performance, support higher waste prevention rates, and enhance nutrient recycling. However, a further analysis of the final compost pathogen content should be run to complete the assessment.

CRediT authorship contribution statement

Juan Pablo Arrigoni: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Gabriela Paladino:** Writing – review & editing, Methodology, Investigation, Formal analysis. **Lucas A. Garibaldi:** Supervision, Resources, Methodology, Formal analysis. **Erik Hedenström:** Writing – review & editing, Funding acquisition. **Wennan Zhang:** Writing – review & editing, Funding acquisition. **Francisca Laos:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition.

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.

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