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DRUM DRYING OF SOURDOUGH: IDENTIFYING OPTIMAL PROCESS CONDITIONS FOR POWDER PRODUCTION AND BREAD APPLICATIONS

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ABSTRACT

In this study, sourdough was produced using a *Lactobacillus brevis* starter culture and subsequently dried using a drum dryer under varying conditions (steam pressures of 2, 2.5, and 3 bar; rotation speeds of 2, 3, 4, and 5 rpm) to obtain sourdough powder. The resulting powders were evaluated for bread production. Optimal drum-drying conditions were identified as 3 bar steam pressure and 2 rpm rotation speed, yielding powders with a moisture content of 8.30% (wb), solubility of 25.80%, and a viable LAB count of 6.3 log CFU/g DM. Breads produced with these powders as a starter exhibited high loaf volume (71.0 cm³) and strong sensory acceptability (6.57/7). For comparison, sourdough was also processed using spray drying, producing powders with lower moisture (4.47% wb), reduced solubility (18.08%), and higher LAB retention (8.2 log CFU/g DM). The effects of both drying methods on bread quality were assessed in terms of technological attributes.

Keywords: Sourdough powder, starter culture, drum dryer, spray dryer, sourdough bread

EKŞİ HAMURUN VALSLİ KURUTUCUDA KURUTULMASI: TOZ ÜRETİMİ VE EKMEK UYGULAMALARI İÇİN EN UYGUN İŞLEM KOŞULLARININ BELİRLENMESİ

ÖZ

Bu çalışmada, *Lactobacillus brevis* starter kültürü kullanılarak üretilen ekşi hamur valsli kurutucuda farklı koşullarda (2, 2.5 ve 3 bar; 2, 3, 4 ve 5 rpm) kurutulmuş ve elde edilen ekşi hamur tozları ekmek üretiminde test edilmiştir. En uygun (optimum) kurutma koşulu 3 bar buhar basıncı ve 2 rpm dönme hızı olarak belirlenmiş, bu koşullarda üretilen tozların nem içeriğinin %8.30 (yb), çözünebilirlik değerinin %25.80 ve LAB sayısının 6.3 log KOB/g KM olduğu gözlemlenmiştir. Valsli kurutucuda optimum koşulda elde edilen tozların maya (starter kültür) olarak kullanımı ile üretilen ekmeklerin

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yüksek hacim (71.0 cm³) ve duyusal kabul edilebilirlik değerine (6.57/7) sahip olduğu görülmüştür. Ekşi hamur ayrıca püskürtmeli kurutucuda da kurutulmuş ve elde edilen tozların nem içeriği %4.47 (yb), çözünebilirlik değeri %18.08 ve LAB sayısı 8.2 log KOB/g KM olarak belirlenmiştir. Her iki kurutma yöntemi ile elde edilen ekşi hamur tozlarının ekmek kalitesi üzerindeki etkileri değerlendirilmiş ve üretilen ekmekler teknolojik özellikler açısından karşılaştırılmıştır.
Anahtar kelimeler: Ekşi hamur tozu, starter kültür, valsli kurutucu, püskürtmeli kurutucu, ekşi hamur ekmeği

INTRODUCTION

Sourdough bread, obtained through the spontaneous fermentation of dough consisting of grain flour and water, is considered as the earliest form of bread known today, dating back to Ancient Egypt. In recent years, the increasing demand for healthier food options has renewed interest in sourdough-based products (Lau et al., 2021). The microflora of sourdough consists of yeasts and lactic acid bacteria (LAB), which produce metabolites such as organic acids, exopolysaccharides, and enzymes that contribute to its distinctive aroma. The use of sourdough in bread production enhances not only flavor and shelf-life but also improves texture and volume (Martin-Garcia et al., 2023).

Sourdough is classified into five types based on its preparation method: Type 0: Prepared as a pre-dough, undergoing spontaneous fermentation for a limited time to allow growth of LAB naturally present in the flour (De Vuyst et al., 2023). Type I: Prepared through spontaneous fermentation of a flour-water mixture at 20–30°C, with daily refreshments (back slopping). Type II: Produced by adding a starter culture, followed by a single-stage fermentation (15–20 hours at 30°C) and a single refreshment step. The starter culture consists of LAB and/or yeast cultures. Type III: Derived from Type II sourdough through drying, making it more stable. The microflora of Type III sourdough includes *Pediococcus pentosaceus*, *L. plantarum*, and *L. brevis*, which are resilient to drying processes (Siepmann et al., 2018). The most commonly used drying methods for Type III sourdough are drum drying and spray drying (Brandt, 2019). Type IV: Mixed sourdough, prepared by initiating with a starter culture and propagated through back-slopping; spontaneous fermentation and microbial interactions can lead to natural selection (Siepmann et al., 2018).

Drying is a widely used technique across food, pharmaceutical, and chemical industries, aiming to reduce water content and extend shelf-life (Türker et al., 2006; Köprüalan, 2019). The process involves moisture removal via evaporation and diffusion, preventing microbial spoilage and enzyme-driven degradation. Microbial growth ceases below 10% moisture content, while levels below 5% help preserve taste, aroma, and nutritional value (Geankoplis, 2006; Altay, 2020).

For starter culture drying, the survival rate of microorganisms is a critical parameter (Vaessen et al., 2019). Several drying methods have been explored for sourdough, including tray drying (Hendek-Ertop et al., 2018; Lafuente et al., 2024), spray drying (Tafti et al., 2013, Reale et al., 2019), freeze-drying (Różyło et al., 2016; De Marco et al., 2025), and refractance window drying (Arslan-Tontul et al., 2024). Spray drying atomizes liquid samples into a hot air chamber, rapidly evaporating moisture. The short processing time minimizes heat-induced deterioration, and evaporative cooling helps prevent Maillard reactions (Ohtake et al., 2020; Martin-Garcia et al., 2023). Drum drying involves direct contact with a heated surface, utilizing latent and sensible heat for evaporation. Drum dryers are available in two designs: Single-drum dryers, where the product is spread in a thin layer over a heated drum. Double-drum dryers, where two parallel, counter-rotating drums process the product, with the gap between the drums adjustable to control film thickness. The thickness of the feed film layer is a crucial parameter that directly affects the quality and characteristics of the final product in drum drying. It influences drying efficiency, moisture content, texture, and rehydration properties of the dried sourdough powder (Brandt, 2019). A thinner film allows for faster drying and better heat transfer, while a thicker film may lead to uneven drying and potential quality deterioration. Optimizing this parameter ensures the desired functional and sensory attributes of the final product. This method is widely applied in baby formula, milk powders, breakfast cereals, fruit and vegetable pulps, mashed potatoes, and dry yeast production (Malekjani et al., 2023).

Drum drying offers high reliability, efficiency, and flavor enhancement via Maillard reactions (Kirchhoff, 2000). However, most previous studies on drum-dried sourdough have focused on its flavor and volatile compounds, with limited research on LAB survival during the process. Given that drum drying is more economical than other drying methods, investigating LAB survival and the suitability of drum-dried sourdough for bread production enhances the originality and significance of this study.

The aim of this study is to optimize the drum drying parameters for sourdough powder production and evaluate its suitability in bread making. The study investigates the effects of steam pressure and drum rotation speed on the physicochemical properties and lactic acid bacteria (LAB) survival in the dried sourdough powder. Additionally, the functionality of the obtained powder is assessed by incorporating it into sourdough bread formulations and analyzing bread quality attributes such as volume, texture, and sensory properties. Furthermore, a comparison with spray drying is conducted to evaluate the economic and functional feasibility of drum drying as an alternative drying method for sourdough preservation.

MATERIAL AND METHOD

Material

In this study, *Lactobacillus brevis* starter culture (Pak Gıda Üretim ve Pazarlama A. Ş., Türkiye) and whole wheat flour (Söke Değirmencilik San. ve Tic. A.Ş., Türkiye) with protein content of 13.2%, moisture content of 14.5%, and ash content of 1.4% were used to produce sourdough. Instant dry yeast (Pak Gıda Üretim ve Pazarlama A. Ş., Türkiye) and salt used for bread baking were obtained from a local market in Türkiye.

Method

Activation and cultivation of the starter culture

The *Lactobacillus brevis* culture, provided in glycerol stock form, was activated by incubation in MRS Broth (pH 5.7±0.2; Merck, Germany) at 30°C for 24 hours following a 10% inoculation. After activation, the culture was further cultivated in MRS Broth, and the cell suspension was obtained by centrifugation (4000g, 10 min), followed by two washes with 0.85% NaCl solution (Khem et al., 2016).

Preparation of sourdough

For sourdough preparation, 120 g of whole wheat flour, 18 mL of cell suspension, and 42 g of water were mixed and incubated at 30°C for 5 hours. Sourdough production was carried out over eight back-slopping steps (Döner, 2017). During each back-slopping step, the dough: flour: water ratio was maintained at 2:2:1 (w/w/w), with 44.4% of the previously prepared dough used as inoculum for the next fermentation cycle.

Drum drying of sourdough

Drum drying of sourdough samples was performed using pilot-scale double drum dryer located at the Ege University, Department of Food Engineering. The drum dryer consisted of two hollow cylinders, each measuring 20 cm in length and 10 cm in diameter. The drying process was conducted under steam pressures of 2, 2.5, and 3 bar, with rotation speeds of 2, 3, 4, and 5 rpm, and a drum opening of 2 mm. Before feeding into the dryer, the sourdough was diluted with distilled water at a 2:1 (w/v) ratio to achieve the desired consistency. The drum opening (2 mm) was considered the thickness of the final dried product.

Spray drying of sourdough

Spray drying of sourdough samples was carried out according to the method of Reale et al. (2019), with slight modifications. In this context, a sourdough suspension (prepared by diluting sourdough with distilled water at a 2:1 (w/v) ratio) was fed into the spray dryer using a peristaltic pump at 25°C. Spray drying was conducted using a laboratory-scale spray dryer (Buchi B-290, Switzerland) under the following conditions:

Aspiration rate: 60%, Airflow rate: 473 L/h, Air pressure: 5 kg/cm², Nozzle diameter: 0.7 mm, Air inlet temperature: 130°C, Air outlet temperature: 60°C. All parameters were maintained constant throughout the process.

Bread production from sourdough powder

Breads were produced using sourdough powders that met the suitable moisture content criteria among those obtained via spray drying and drum drying. The bread formulation was adapted from Lattanzi et al. (2014) with modifications. The amount of sourdough powder used was adjusted to match the dry matter content of fresh yeast typically included in the formulation. The powder was then incorporated into a mixture of whole wheat flour of 41.1 g, dry yeast of 1.05 g, water of 23.5 g, salt of 0.83 g. To evaluate the impact of sourdough powder, a control group was prepared without its addition. The amount of water added during bread production was adjusted according to the water absorption capacity of the flour. Farinograph analysis revealed that the water absorption capacity of the whole wheat flour was 65%.

Dough samples were kneaded for 10 minutes initially, followed by a three-stage fermentation process: 45 minutes of fermentation, 1 minute of kneading, 45 minutes of fermentation, 1 minute of kneading and 75 minutes of fermentation. After fermentation, the dough was shaped and baked for 35 minutes at 180°C in a conventional oven.

Analysis

Moisture content and water activity

Sourdough, sourdough powder, and bread samples were analyzed for moisture content according to AOAC 925.10 standards, using a stove set to 105°C. Water activity of sourdough powder and bread samples was measured using a water activity probe (Testo AG400), calibrated to ±0.001 precision (Hajar-Azhari, 2024).

pH and total titratable acidity (TTA)

Sourdough and sourdough powder samples were homogenized with distilled water at a 1:9 (w/v) ratio and analyzed for pH using a pH meter (pH7110, InoLab). The pH of the mixture was adjusted to 8.3 by titrating with 0.1 N NaOH (Reale et al., 2019). Total titratable acidity was calculated using Equation (1) and expressed as lactic acid percentage.

$$TTA\ (\%) = \frac{V\ x\ 0.009}{m}\ x\ 100 \qquad (1)$$

Where; V: 0.1 N NaOH used in titration (ml); m: Sample weight used in titration (g)

Bulk and tapped density

Bulk density of the sourdough powder samples was analyzed by the weight/volume ratio of powders filled into a graduated cylinder without any space between the particles and without applying force. Tapped density was determined by tapping the graduated cylinder manually on a surface until a constant volume was reached (Bhandari et al., 1992).

Solubility

Sourdough powders were diluted at a 1:25 (w/v) ratio with distilled water and homogenized at 3000 rpm for 5 minutes. The mixture was then centrifuged at 3000 rpm for 5 minutes, and the fluid at the top was collected and dried in a stove at 105°C for 4 hours. The solubility value was calculated based on the weight difference, expressed as a percentage (Cano-Chauca et al., 2005).

Lactic acid bacteria count

Sourdough and sourdough powder samples were homogenized with a 0.85 % NaCl solution at a 1:9 (w/v) ratio and prepared through serial dilutions. One milliliter of each suitable sample was inoculated onto MRS Agar (pH 5.7±0.2; Merck, Germany) using a double-layer pour-plate method. Samples were incubated for 3 days at 30-35°C, and colonies were counted after the incubation period (Caglar et al., 2021). Results were expressed as CFU/g DM.

Color properties

Color values (L* (brightness, darkness), a* (redness, greenness), b* (yellowness, blueness)) of sourdough, sourdough powder, and bread samples were measured using a Minolta CR-300 color meter and recorded according to Hunter CIE Lab and Color Flex system (Shahabi et al., 2014). The device was calibrated with a white plate prior to measurements. The following parameters were calculated:

$$\Delta E = \sqrt{\Delta L^2 + \Delta a^2 + \Delta b^2} \quad (2)$$

$$C = (a_t^2 + b_t^2)^{0.5} \quad (3)$$

$$Hue = \tan^{-1}\left(\frac{b_t}{a_t}\right) \quad (4)$$

$$BI = \frac{\left[100\,x\left(\frac{a_t+1.75L_t}{5.645L_t+a_t-3.012b_t}-0.31\right)\right]}{0.17} \quad (5)$$

Water absorption capacity of flour
To formulate the bread recipe, the water absorption capacity of whole wheat flour was determined using a farinograph (Brabender, Mod. PL Nr.952065, Duisburg, Germany) according to ICC Standard Nr. 115/1 (Altınel and Ünal, 2017).

Cooking loss
The cooking loss of bread samples was determined by calculating the difference in weight before and after baking, expressed as a percentage (Alvarez-Jubette et al., 2010).

Crust thickness
10 mm thick, uniform cutaways were taken from bread samples, and the crust thickness was measured using calipers. Measurements were taken from three different points (Hendek-Ertop, 2014).

Bread volume
To determine the volume of bread samples, rapeseeds were filled into a glass vessel of known volume to analyze their bulk volume, which was calculated based on the volume of the vessel and the weight of the seeds. The bread volume was determined by weighing the bread samples individually, placing them into a glass vessel of known weight, and weighing again. The volume of bread was calculated using rapeseeds of known weight and volume (Parenti et al., 2020).

Texture profile analysis
Using a cylindrical probe (P/36R) and a texture analyzer (TA-XT2, Stable Micro Systems, Haslemere, UK), the hardness, springiness, chewiness, cohesiveness, and gumminess values of the bread samples were determined on the inner part of the bread after a 2-hour resting period. The pre-test, test, and post-test speeds were set at 2.0 mm/sec, with a test distance of 5 mm and a trigger force of 5.0 g. Ten measurements were taken for each sample, and the average values were calculated (Liu et al., 2024).

Sensory evaluation
The sensory evaluation of bread samples was conducted by 10 semi-trained panelists based on crust color, inside color, porosity, appearance, taste, and overall acceptability. A 1-7 scoring scale was used for multiple comparisons (Altuğ-Onoğur & Elmacı, 2011).

Statistical analysis
Statistical analyses of sourdough powder samples dried in a drum dryer, and the produced bread samples were performed using Duncan's variance analysis in SPSS V25.0 (IBM, USA) statistical software.
Sourdough powder and bread production were carried out in duplicate. All analyses were performed in duplicate, except for colour measurements and texture analysis, which were conducted in five and ten replicates, respectively.

RESULTS AND DISCUSSION

Physicochemical and microbiological properties of drum dried sourdough powders and selection of optimum conditions
The physicochemical and microbiological properties of sourdough powders are summarized in Table 1a and Table 1b. The moisture content, pH, and total titratable acidity (TTA) of the sourdough produced after eight back-slopping cycles (30°C, 4 hours) with *Lactobacillus brevis* starter culture were determined as 38.75%±0.43 (wb), 3.95±0.002, and 1.58%±0.15, respectively. The production of lactic acid as a metabolite of the starter culture contributes to increased acidity, thereby lowering the pH. Similar results were reported in a study where sourdough samples fermented with *L. brevis* exhibited a minimum pH value of 3.86 over a seven-day fermentation period (Akgün, 2007). Additionally, Alkay (2017) reported TTA values ranging between 1.01% and

1.52% for sourdough samples produced with *Lactobacillus rossiae, L. plantarum, L. brevis*, and *Weissella cibaria* strains after 24 hours, which aligns with the findings of this study. The lactic acid bacteria count in sourdough samples was determined as 9.9 log CFU/g DM. Regarding colour properties, L*, a*, and b* values were recorded as 71.21±1.08, 5.28±0.41, and 24.12±0.90, respectively.

Table 1a. Physicochemical and microbiological properties of sourdough powders produced by a drum dryer under different operating conditions and a spray dryer

	*SP (bar)	**DS (rpm)	Moisture Content (%, wb)	Water Activity	Bulk Density (kg/m³)	Tapped Density (kg/m³)	pH	TTA (%)	LAB (log CFU/g DM)
DRUM DRIED	2	2	$13.02^{b}\pm0.05$	$0.766^{b}\pm0.010$	$187.44^{bc}\pm1.83$	$244.66^{bc}\pm6.12$	$4.06^{a}\pm0.052$	$1.65^{e}\pm0.05$	7.2±0.01
		3	$25.35^{f}\pm0.53$	$0.944^{fg}\pm0.007$	$238.88^{e}\pm4.59$	$272.86^{de}\pm9.88$	$4.04^{a}\pm0.085$	$1.62^{e}\pm0.04$	-
		4	$27.09^{g}\pm0.24$	$0.951^{fg}\pm0.003$	$291.81^{f}\pm6.52$	$310.41^{f}\pm7.49$	$3.99^{a}\pm0.052$	$1.44^{b}\pm0.08$	-
		5	$37.20^{j}\pm0.63$	$0.960^{g}\pm0.001$	$327.45^{g}\pm10.98$	$334.60^{g}\pm6.60$	$3.98^{a}\pm0.047$	$1.35^{a}\pm0.00$	-
	2.5	2	$9.18^{a}\pm0.04$	$0.693^{a}\pm0.013$	$143.96^{a}\pm4.56$	$219.56^{a}\pm4.79$	$3.90^{a}\pm0.067$	$2.16^{g}\pm0.10$	5.5±0.15
		3	$18.82^{d}\pm0.23$	$0.829^{c}\pm0.010$	$178.33^{b}\pm1.56$	$227.05^{ab}\pm1.07$	$3.96^{a}\pm0.004$	$2.16^{c}\pm0.10$	-
		4	$25.30^{f}\pm0.13$	$0.866^{d}\pm0.015$	$193.49^{bc}\pm4.11$	$238.38^{abc}\pm1.83$	$3.95^{a}\pm0.018$	$2.03^{d}\pm0.05$	-
		5	$35.97^{i}\pm0.48$	$0.920^{ef}\pm0.011$	$215.04^{d}\pm3.37$	$289.66^{e}\pm2.30$	$3.93^{a}\pm0.002$	$1.94^{f}\pm0.05$	-
	3	2	$8.25^{a}\pm0.05$	$0.660^{a}\pm0.024$	$176.39^{b}\pm3.21$	$241.68^{bc}\pm3.43$	$4.00^{a}\pm0.001$	$1.98^{i}\pm0.10$	6.3±0.01
		3	$16.95^{c}\pm0.64$	$0.837^{cd}\pm0.010$	$186.98^{bc}\pm3.22$	$248.60^{bc}\pm4.34$	$3.99^{a}\pm0.007$	$1.76^{h}\pm0.05$	-
		4	$23.82^{e}\pm0.61$	$0.905^{e}\pm0.006$	$197.65^{c}\pm1.35$	$255.21^{cd}\pm6.54$	$3.96^{a}\pm0.002$	$1.71^{j}\pm0.00$	-
		5	$33.91^{h}\pm0.17$	$0.924^{efg}\pm0.002$	$223.47^{de}\pm9.36$	$281.11^{e}\pm9.44$	$3.97^{a}\pm0.020$	$1.67^{g}\pm0.05$	-
SPRAY DRIED			4.47±0.37	0.337±0.001	449.96±6.40	534.74±5.80	4.18±0.012	1.40±0.08	8.2±0.01

*SP: Steam Pressure, **DS: Drum Rotation Speed. Microbiological analyses were conducted on experimental groups with suitable powder properties (moisture content <13%). Different letters within a column indicates statistically significant differences at $P<0.05$ between values.

The moisture content of sourdough powders produced by drum drying remained below 13% only in samples dried at 2, 2.5, and 3 bar steam pressure with a 2 rpm rotation speed, with water activity values ranging from 0.660 to 0.960 (Table 1a). An evaluation of the moisture content and water activity results revealed that higher steam pressure and lower rotational speed enhanced the drying efficiency, leading to sourdough powders with lower moisture content and water activity values ($P<0.05$). Conversely, an increase in drum rotation speed reduced drying efficiency, resulting in insufficiently dried sourdough powders. Among the tested conditions, sourdough powders dried at 2, 2.5, and 3 bar steam pressure with 2 rpm rotation speed exhibited the most desirable moisture content values. Moisture content and water activity are key indicators of drying efficiency; higher-than-expected values indicate an insufficient drying process. Similar trends were observed in a study by Topuz & Pazır (2017), where increasing steam pressure and decreasing drum rotation speed resulted in apple purée powders with lower moisture content.

An analysis of bulk and tapped density data revealed that sourdough powders produced at 2.5 bar steam pressure and 2 rpm rotation speed exhibited the lowest values ($P<0.05$). Bulk and tapped densities are crucial parameters for assessing the physical properties of powdered products. Bulk density depends on particle type and the interstitial space between particles. Even if two particles have the same weight, differences in particle size influence bulk density due to varying degrees of space between them. A decrease in particle size within a bulk system generally leads to an increase in compressed volume (Altay, 2020). The pH and total titratable acidity (TTA) values of sourdough powders ranged from 3.93 to 4.06 and 1.35% to 2.16%, respectively (Table 1a). Among the tested conditions, the sourdough powder produced at 2.5 bar steam pressure and 2 rpm rotation speed was the most acidic in terms of both pH and TTA. Insufficiently dried samples, caused by higher drum rotation speeds, exhibited lower acidity levels, likely due to retained moisture reducing the concentration of acidic compounds. In contrast, samples dried at 2 rpm rotational speed, which met the desired powder properties, showed higher acidity values ($P<0.05$). Figure 1 presents the solubility of sourdough powders produced under different drying conditions. Properly dried powders are expected to have high solubility; however, due to the presence of gluten from wheat flour, sourdough powders tend to form suspensions rather than fully dissolving in water. Moreover, gluten coagulates at 70°C, forming a pseudo-solid film (Göncü, 2011). Given the high temperatures used in drum drying, gluten coagulation likely contributed to the lower solubility of sourdough powders.

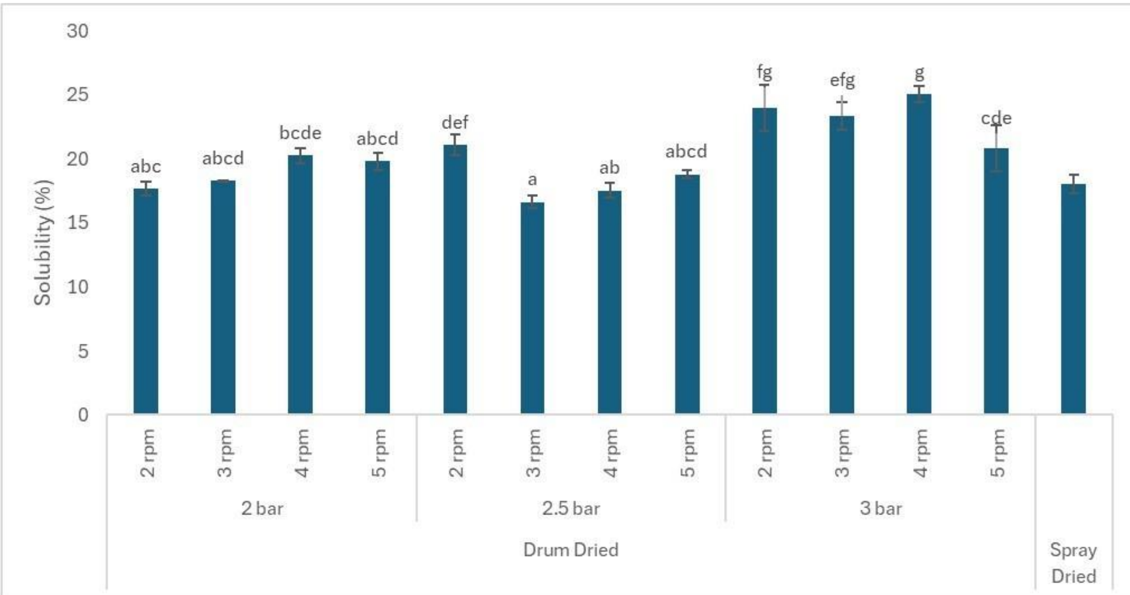

Figure 1. Solubility of sourdough powders produced by a drum dryer under different operating conditions and a spray dryer

*Different letters within a column indicates statistically significant differences at $P<0.05$ between values.

The solubility values of sourdough powders produced in this study ranged from 16.66% to 25.07% (Figure 1). Among the tested conditions, the highest solubility was observed in the sample drum-dried at 3 bar steam pressure and 2 rpm rotation speed. Statistical analysis of samples with suitable powder properties indicated that solubility decreased as moisture content increased ($P<0.05$). Colour analysis of properly dried sourdough powders showed higher L (brightness) values* compared to insufficiently dried samples. The Browning Index (BI), which reflects the degree of darkening due to factors such as burning or improper drying was higher in samples with excessive moisture content, suggesting localized browning (Table 1b).

A high lactic acid bacteria count is desirable in sourdough powders, as it indicates better microbial viability. Sourdough powders produced at 2 rpm rotation speed and 2, 2.5, and 3 bar steam pressure, which met the desired powder characteristics, were analysed for lactic acid bacteria viability. The lowest bacterial viability was recorded at 2.5 bar steam pressure, while the highest was observed at 2 bar steam pressure. This suggests that increasing steam pressure at a constant rotational speed raises drum temperatures, leading to reduced bacterial viability. Overall, a 2–4 log unit reduction in lactic acid bacteria count was observed in sourdough powders dried at 2 rpm rotational speed. When considering all the results, the most suitable drying conditions for sourdough powder production were determined to be 3 bar steam pressure and 2 rpm rotation speed.

Table 1b. Physicochemical and microbiological properties of sourdough powders produced by a drum dryer under different operating conditions and a spray dryer

	*SP (bar)	**DS (rpm)	L*	a*	b*	Chroma	Hue	BI	ΔE
DRUM DRIED	2	2	$81.02^{c}\pm1.21$	$2.32^{abcd}\pm0.33$	$13.72^{ab}\pm0.34$	$13.92^{abc}\pm0.38$	$80.42^{de}\pm1.17$	$20.29^{ab}\pm1.09$	$14.61^{cd}\pm1.11$
		3	$71.31^{b}\pm4.83$	$3.18^{bcde}\pm0.44$	$14.18^{ab}\pm1.26$	$14.54^{a}\pm1.26$	$77.32^{de}\pm1.66$	$25.11^{abcd}\pm2.55$	$11.07^{abcd}\pm1.5$
		4	$67.27^{a}\pm4.33$	$3.88^{ef}\pm0.45$	$14.84^{ab}\pm0.87$	$15.34^{abc}\pm0.86$	$75.33^{abc}\pm1.77$	$28.83^{cd}\pm2.70$	$10.80^{abc}\pm2.09$
		5	$67.11^{a}\pm3.38$	$3.41^{ef}\pm0.80$	$14.39^{ab}\pm2.26$	$14.79^{abc}\pm2.36$	$76.82^{ab}\pm1.51$	$27.46^{cd}\pm4.70$	$11.13^{abc}\pm2.58$
	2.5	2	$79.65^{bc}\pm1.12$	$2.13^{ab}\pm0.10$	$13.01^{a}\pm0.40$	$13.18^{ab}\pm0.40$	$80.73^{ef}\pm0.31$	$19.43^{a}\pm0.72$	$14.34^{bcd}\pm0.69$
		3	$75.8^{b}\pm5.56$	$2.16^{a}\pm0.34$	$13.17^{a}\pm0.74$	$13.35^{a}\pm0.77$	$80.72^{ef}\pm1.19$	$20.98^{ab}\pm3.05$	$13.28^{abcd}\pm0.99$
		4	$72.39^{b}\pm6.12$	$2.81^{abcd}\pm0.78$	$14.71^{ab}\pm0.87$	$14.99^{abc}\pm0.89$	$79.22^{ef}\pm2.90$	$25.23^{abc}\pm2.15$	$11.16^{abcd}\pm2.21$
		5	$74.98^{b}\pm3.97$	$1.93^{a}\pm0.67$	$14.84^{b}\pm2.06$	$14.98^{bc}\pm2.07$	$82.59^{f}\pm2.41$	$23.58^{bcd}\pm3.86$	$11.14^{ab}\pm2.34$
	3	2	$81.97^{c}\pm0.78$	$2.16^{abc}\pm0.23$	$13.66^{ab}\pm0.38$	$13.83^{abc}\pm0.39$	$81.04^{ef}\pm0.89$	$19.78^{ab}\pm0.71$	$15.34^{d}\pm0.64$
		3	$66.60^{a}\pm8.98$	$3.75^{de}\pm0.81$	$15.11^{ab}\pm0.85$	$15.58^{abc}\pm0.83$	$76.05^{bcd}\pm3.02$	$29.96^{cd}\pm5.04$	$12.88^{abcd}\pm3.00$
		4	$68.13^{a}\pm1.18$	$4.32^{f}\pm0.50$	$16.23^{b}\pm0.73$	$16.78^{c}\pm0.83$	$75.42^{a}\pm1.09$	$31.31^{d}\pm2.15$	$8.62^{a}\pm0.74$
		5	$69.04^{a}\pm10.47$	$2.97^{cde}\pm1.47$	$13.53^{ab}\pm1.54$	$13.91^{abc}\pm1.65$	$77.87^{cde}\pm5.68$	$25.35^{cd}\pm6.37$	$14.36^{abcd}\pm3.67$
SPRAY DRIED			95.88 ± 0.28	0.07 ± 0.03	4.46 ± 0.26	4.46 ± 0.26	89.11 ± 0.43	4.70 ± 0.27	31.98 ± 0.35

*SP: Steam Pressure, **DS: Drum Rotation Speed. Microbiological analyses were conducted on experimental groups with suitable powder properties (moisture content <13%). Different letters within a column indicates statistically significant differences at $P<0.05$ between values.

Comparison of sourdough powders obtained via spray drying and drum drying

The physicochemical and microbiological properties of spray-dried sourdough powders are presented in Table 1a and Table 1b. The moisture content and water activity of spray-dried samples were determined as 4.47±0.37% (wb) and 0.337±0.001, respectively. These values are significantly lower than those of drum-dried samples, indicating that spray drying is more effective in reducing moisture and achieving lower water activity. Additionally, spray-dried powders exhibited better powder characteristics, as reflected in their higher bulk density (449.96±6.40 kg/m³) and tapped density (534.74±5.80 kg/m³) compared to drum-dried samples. This suggests that spray drying leads to better particle packing and flowability, which are important for storage and handling. In terms of colour properties, L* values (95.88±0.28) of spray-dried powders were significantly higher, indicating brighter and lighter-coloured powders, while browning index (BI) values (4.70±0.27) were lower compared to drum-dried powders. This suggests that Maillard reactions and browning effects were minimized in spray drying due to shorter exposure to high temperatures. The viability of lactic acid bacteria (LAB) in spray-dried sourdough powders was recorded as 8.2±0.01 log CFU/g DM, with only a 1-log unit reduction from the initial LAB count before drying. This retention is notably higher than in drum drying, where thermal stress during contact drying significantly reduces bacterial viability.

Similar studies have reported more reductions that are significant in LAB viability during spray drying. For instance, in a study where sourdough was spray-dried using an inlet air temperature of 180°C and an outlet air temperature of 90°C, LAB viability decreased from 2.0×10^{9} CFU/g to 2.0×10^{5} CFU/g when the final moisture content was reduced to approximately 4-5% (Tafti et al., 2013). Similarly, Caglar et al. (2021) reported that sourdough was spray-dried (air inlet temperature 160 °C, outlet temperature 90 °C) until the moisture content dropped below 5%, resulting in a decline in LAB viability from 9.7 log CFU/g to 5.0 log CFU/g. However, in the present study, LAB viability was found to be significantly higher than in similar studies, suggesting that optimized spray drying conditions in this study were more favourable for LAB survival. The lower bacterial inactivation observed in this study could be attributed to controlled drying parameters, protective matrices within the sourdough, or strain-specific resistance to drying processes (Corsetti, 2012; Reale et al., 2019).

Properties of bread produced with sourdough powders

The physical properties of breads produced with spray-dried and drum-dried sourdough powders under different drying conditions are presented in Table 2. The moisture content, water activity, and crust thickness of breads made with drum-dried sourdough powders showed no statistically significant differences (p>0.05) (Table 2). In contrast, breads produced with spray-dried sourdough powders exhibited greater variations in water content and crust thickness. However, the difference in moisture content between breads made with spray-dried powders, control samples, and drum-dried powders produced under optimal conditions (3 bar, 2 rpm) was not statistically significant (p>0.05) (Table 2).

Table 2. Physical properties of breads made with sourdough powders produced via drum drying under different operating conditions and spray drying.

	*SP (bar)	**DS (rpm)	Moisture Content (%, wb)	Water Activity	Cooking Loss (%)	Crust Thickness (mm)	Hardness (N)	Springiness	Chewiness (N)	Cohesiveness	Gumminess
CONTROL			$32.30^{A}\pm0.73$	$0.930^{A}\pm0.004$	$15.07^{B}\pm0.06$	$2.02^{A}\pm0.00$	$9.74^{A}\pm1.00$	$0.86^{A}\pm0.03$	$5.82^{A}\pm0.33$	$0.69^{AB}\pm0.02$	$6.82^{A}\pm0.59$
DRUM DRIED	2		$32.24^{a}\pm0.42$	$0.941^{a}\pm0.001$	$13.84^{b}\pm0.29$	$2.25^{a}\pm0.05$	$54.07^{b}\pm1.64$	$0.85^{a}\pm0.04$	$31.25^{b}\pm0.38$	$0.67^{a}\pm0.02$	$36.45^{b}\pm0.25$
	2.5	2	$32.89^{a}\pm0.50$	$0.936^{a}\pm0.002$	$12.23^{a}\pm0.42$	$2.36^{a}\pm0.16$	$42.05^{a}\pm1.00$	$0.87^{a}\pm0.05$	$25.68^{a}\pm0.71$	$0.70^{a}\pm0.00$	$29.35^{a}\pm0.62$
	3		$32.22^{a/A}\pm0.60$	$0.935^{a/A}\pm0.003$	$14.33^{b/B}\pm0.12$	$2.20^{a/B}\pm0.01$	$43.45^{a/C}\pm1.74$	$0.88^{a/A}\pm0.01$	$27.87^{a/C}\pm1.69$	$0.72^{a/B}\pm0.01$	$31.57^{a/C}\pm1.42$
SPRAY DRIED			$32.87^{A}\pm0.42$	$0.951^{B}\pm0.004$	$11.31^{A}\pm0.34$	$2.17^{B}\pm0.12$	$23.52^{B}\pm0.63$	$0.82^{A}\pm0.06$	$12.43^{B}\pm0.16$	$0.66^{A}\pm0.01$	$9.85^{B}\pm0.04$

*SP: Steam Pressure, **DS: Drum Rotation Speed. Different letters within a column indicates statistically significant differences at $P<0.05$ between values. Lowercase letters indicate statistically significant differences between drum-dried samples while uppercase letters indicate statistically differences between control, spray and drum dried (under the most suitable conditions) samples.

When evaluating bread volume (Figure 2) and cooking loss (Table 2), the highest values were observed in breads produced with sourdough powders dried at 3 bar steam pressure and 2 rpm rotational speed. However, spray-dried sourdough powders resulted in breads with even higher volume compared to both drum-dried samples and the control group (Figure 2). Additionally, cooking loss was found to be lowest in breads made with spray-dried powders (Table 2), indicating improved baking performance.

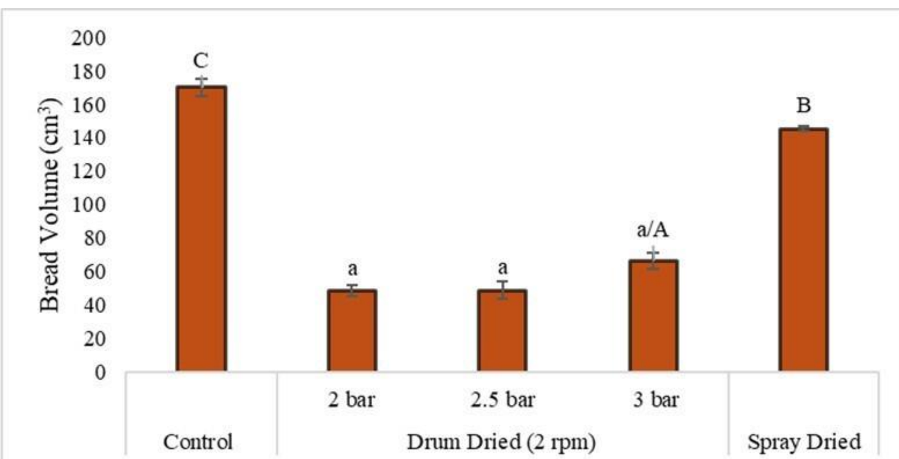

Figure 2. Volumes of breads made with sourdough powders produced via drum drying with different operating conditions, spray drying and control

*Different letters within a column indicates statistically significant differences at $P<0.05$ between values. Lowercase letters indicate statistically significant differences between drum-dried samples while uppercase letters indicate statistically differences between control, spray and drum dried (under the most suitable conditions) samples.

The textural properties of breads produced using sourdough powders from drum drying (under different conditions) and spray drying are presented in Table 2. The highest hardness value was observed in breads made from sourdough powders dried at 2 bar steam pressure and 2 rpm rotational speed ($P<0.05$). Breads produced with sourdough powders from 2.5 and 3 bar steam pressure at 2 rpm exhibited similar hardness and chewiness values, indicating consistent textural characteristics under these drying conditions. Spray-dried sourdough powders resulted in softer breads, with hardness values lower than drum-dried samples but higher than the control. The highest cohesiveness values were recorded in breads made with sourdough powders dried at 3 bar steam pressure and 2 rpm rotational speed.

Chewiness values followed a similar trend to hardness, where breads with spray-dried powders were softer and less chewy than drum-dried samples but chewier than the control. The hardness values of sourdough powder breads in this study align with previous reports, where values ranged between 20.73-56.54 N (Olojede et al., 2020). Breads produced with *L. brevis* starter culture and prebiotic additives were reported to have chewiness values between 4.11-15.37 N (Alkay, 2017), similar to the chewiness trends observed in this study. As expected, sourdough breads exhibit greater chewiness compared to standard yeast-leavened breads.

The colour properties of breads produced with sourdough powders dried by drum drying (under different conditions) and spray drying are presented in Table 3. The L*, a*, and b* values for both inside and crust colour of bread samples made with drum-dried sourdough powders showed no significant differences among drying conditions ($P>0.05$). This suggests that varying steam pressure and rotational speed during drum drying did not significantly affect the colour properties of the resulting bread. Spray-dried samples exhibited higher inside L* values than both control and drum-dried samples, indicating a lighter crumb colour. The crust L* values showed no significant difference ($P>0.05$) between spray-dried and drum-dried samples. The crust BI (Browning Index) values for drum-dried samples were found to be the lowest, suggesting less browning compared to spray-dried or control samples. These results indicate that spray drying may lead to a brighter crumb colour, while drum drying results in less browning on the crust.

Table 3. Colour properties of breads produced using sourdough powders from drum drying (under different conditions) and spray drying

	*SP (bar)	**DS (rpm)	*Inside* L*	a*	b*	Chroma	Hue	BI	ΔE
CONTROL			57.67^{A}±2.77	3.93^{B}±0.25	18.54^{A}±0.64	57.67^{A}±2.77	18.96^{B}±0.62	78.02^{B}±0.88	43.16^{B}±2.16
DRUM DRIED	2		52.60^{a}±2.11	5.19^{a}±0.09	18.94^{a}±0.94	19.62^{a}±0.92	74.92^{a}±0.56	50.94^{a}±1.95	19.33^{a}±2.3
	2.5	2	52.51^{a}±1.34	5.36^{a}±0.32	19.17^{a}±0.41	19.91^{a}±0.43	74.39^{a}±0.85	52.14^{a}±2.82	19.36^{a}±1.2
	3		52.63$^{a/A}$±2.10	5.61$^{a/C}$±0.40	19.51$^{a/A}$±0.73	20.30$^{a/A}$±0.75	73.97$^{a/A}$±1.00	53.35$^{a/B}$±3.25	19.16$^{a/B}$±2.1
SPRAY DRIED			73.69^{B}±0.57	2.13^{A}±0.26	17.24^{A}±0.67	17.37^{A}±0.69	82.97^{C}±0.75	28.23^{A}±1.47	7.99^{A}±0.75
	*SP (bar)	**DS (rpm)	*Crust* L*	a*	b*	Chroma	Hue	BI	ΔE
CONTROL			66.82^{A}±5.50	5.98^{A}±2.30	23.03^{B}±3.43	66.82^{B}±5.50	23.83^{A}±3.89	75.88^{AB}±3.29	49.63^{A}±15.58
DRUM DRIED	2		62.71^{a}±5.57	5.20^{a}±1.21	16.41^{ab}±2.91	17.22^{ab}±3.12	72.62^{a}±1.52	36.92^{ab}±9.71	12.83^{a}±1.3
	2.5	2	60.87^{a}±4.56	5.74^{a}±1.47	19.74^{b}±4.74	20.56^{b}±4.94	73.81^{a}±1.42	47.14^{b}±15.83	12.71^{a}±1.8
	3		61.85$^{a/A}$±3.75	5.17$^{a/A}$±1.51	16.92$^{a/A}$±4.25	17.70$^{a/A}$±4.49	73.14$^{a/A}$±1.68	38.58$^{a/A}$±13.6	12.89$^{a/B}$±1.6
SPRAY DRIED			69.51^{A}±1.47	5.45^{A}±0.95	27.45^{B}±0.61	28.88^{B}±0.51	78.76^{A}±2.05	54.88^{B}±1.16	4.02^{A}±0.82

*****SP: Steam Pressure, ******DS: Drum Rotation Speed. Different letters within a column indicates statistically significant differences at P<0.05 between values. Lowercase letters indicate statistically significant differences between drum dried samples while uppercase letters indicate statistically differences between control, spray and drum dried (under the most suitable conditions) samples.

Sensory evaluation scores of breads produced using sourdough powder from drum drying and spray drying are given in Figure 3.

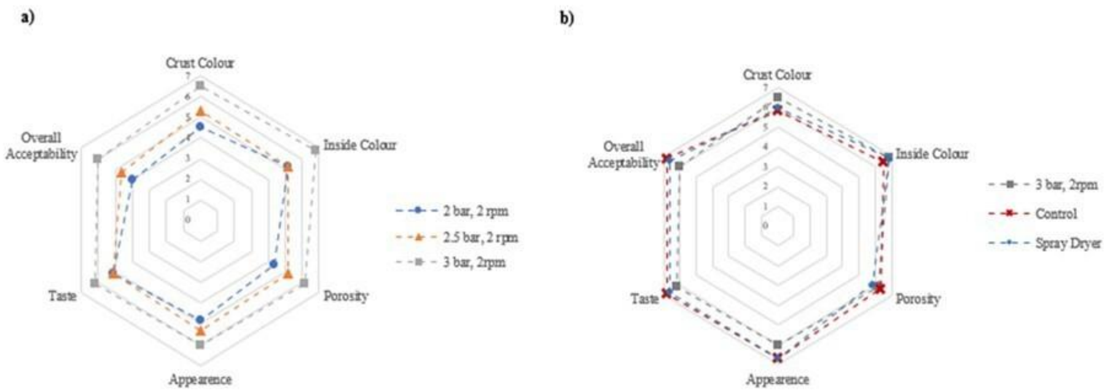

Figure 3. Sensory evaluation scores of sourdough powder breads produced by drum drying a) under different operating conditions b) with most suitable operating conditions, spray drying and control bread

When the sensory evaluation scores of breads produced with sourdough powders are examined (Figure 3a, 3b), the differences between samples were statistically insignificant ($P>0.05$), indicating that all drum-dried sourdough powders produced breads with comparable sensory properties. However, breads produced with sourdough powders obtained at 3 bar steam pressure and 2 rpm scored higher across all sensory attributes, including texture, taste, aroma, and overall acceptability. These results suggest that 3 bar, 2 rpm is the most suitable drum-drying condition for producing sensory-appealing sourdough breads.

The difference between breads made with spray-dried and drum-dried sourdough powders (3 bar, 2 rpm) was statistically insignificant ($P>0.05$) (Fig 3b). This indicates that both drying methods yielded similar sensory characteristics, supporting the feasibility of drum drying as an alternative to spray drying. High scores were observed for all sourdough samples, confirming their favourable sensory properties and consumer acceptability.

CONCLUSION

With the increasing consumer preference for healthier and traditional food products, the demand for sourdough bread has risen significantly. The symbiotic relationship between lactic acid bacteria and yeasts during sourdough fermentation enhances its nutritional value and quality. However, conventional sourdough preparation is a time-consuming process. This study aimed to develop sourdough powder through drum drying, enabling more efficient and consistent sourdough bread production while ensuring sustainability and quality control. The effects of different drying parameters; steam pressure (2, 2.5, and 3 bar) and rotational speed (2, 3, 4, and 5 rpm) were evaluated.

Higher steam pressure (3 bar) and lower rotational speed (2 rpm) improved drying efficiency, leading to sourdough powders with lower moisture content (<13%), desirable water activity, and better solubility. Insufficiently dried samples exhibited lower pH values, while well-dried powders had improved colour (higher L* values) and solubility. Despite drying, lactic acid bacteria retained viability with only a 3-log-unit reduction, reaching 6.3 log CFU/g DM, indicating that the drying process was suitable for maintaining probiotic functionality. Among the breads produced using drum-dried sourdough powders, those obtained under the optimal conditions (3 bar, 2 rpm) exhibited better volume, texture, and sensory scores compared to other experimental groups. Although breads made with spray-dried sourdough exhibited slightly better technological properties (volume, texture, colour, etc.) than those produced with optimally drum-dried powders, both were comparable in terms of sensory attributes. The most suitable drying conditions produced breads with superior colour, porosity, taste, and overall acceptability among panellists.

In conclusion, despite certain limitations such as slightly reduced loaf volume and lower microbial viability due to direct contact with the hot drum surface, drum drying remains a practical and efficient alternative to spray drying. It offers simpler operation, good microbial stability, and functional properties comparable to spray-dried powders, while supporting the production of high-quality sourdough bread that aligns with consumer demand for healthy and traditional baked products.

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AUTHORS' CONTRIBUTION
Özge Filiz: investigation, carried out the experiments and wrote the manuscript; Özgül Altay and Özgün Köprüalan-Aydın: investigation and methodology; Figen Ertekin-Kaymak: investigation, writing-review and editing, supervision.

CONFLICT OF INTEREST
The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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