




Cinnamon-enriched chocolate pralines as a delivery system for *Lactocaseibacillus rhamnosus* CRL1505: viability and digestive stability

Marianna Bozzetti^a, Eleonora Galli^a, Claudia Cortimiglia^a, Ernesto Carrega^a,
 Mariasole Cervini^a, Paolo Cernuschi^b, Daniela Bassi^{a,*} 

^a Department for Sustainable Food Process – DiSTAS, Università Cattolica del Sacro Cuore, Piacenza, Cremona, Italy

^b Sacco srl, Cadorago, CO, Italy

ARTICLE INFO

Keywords:

Chocolate
 Cinnamon
 Functional food
 Lactic acid bacteria
 Probiotics

ABSTRACT

The demand for functional foods is rapidly increasing, particularly in the confectionery sector. Cinnamon, a natural spice rich in polyphenols, exhibits antioxidant, anti-inflammatory, and antimicrobial properties, making it a valuable addition to health-oriented foods. *Lactocaseibacillus rhamnosus* CRL1505 is a probiotic strain known for its immunomodulatory effects, notably in reducing respiratory infections in children. This study aimed to develop milk chocolate pralines enriched with cinnamon and fortified with CRL1505 strain, in order to assess the impact of cinnamon on probiotic viability during storage and simulated digestion.

Two praline variants were formulated: one containing only CRL1505 and the same but supplemented with 3.4 % cinnamon powder. Products were stored at 25 °C for 120 days and analyzed every 30 days for probiotic survival and physicochemical parameters. Microbiological stability was evaluated at the beginning and at the end of the storage period. To assess the probiotic resistance to simulated gastrointestinal digestion, the standardized INFOGEST *in vitro* human digestion static protocol was implied immediately at the end of production, and after 120 days.

Both formulations demonstrated to be microbiologically stable throughout storage. Cinnamon supplementation did not adversely affect probiotic viability during the 120 day-storage period. Simulated digestion confirmed over 77 % survival across all digestive phases, even after extended storage.

These findings suggest that incorporating cinnamon into probiotic chocolate confections does not drastically compromise probiotic viability and offer additional flavor. The combination of CRL1505 and cinnamon presents a promising approach for developing shelf-stable, health-oriented confectionery products.

1. Introduction

Functional foods are defined as foods that provide health benefits beyond basic nutrition. These foods often contain bioactive compounds or nutrients that can enhance health and mitigate disease risk. Probiotics, defined by the World Health Organization (WHO) as “live microorganisms which when administered in adequate amounts confer a health benefit on the host,” are a prominent category of bioactive components within functional foods (Fiocco et al., 2020; Mordor Intelligence, 2025; Tarahi et al., 2024). These beneficial microbes, primarily from the genera *Lactobacillus* and *Bifidobacterium*, are well-known for their role in promoting gut health (Hossain et al., 2021).

Recent research has increasingly focused on the role of probiotics in supporting immune function and reducing infection risk, particularly

among children, a population highly susceptible to respiratory tract infections (RTIs), which remain a leading cause of global pediatric morbidity and mortality (Liu et al., 2013). Numerous studies indicate that specific probiotic strains can decrease the incidence, severity, and duration of RTIs by enhancing mucosal and systemic immune responses (Villena et al., 2012; Wang et al., 2016). For instance, a randomized clinical trial reported that a probiotic mixture containing *Bifidobacterium breve* M-16V, *Bifidobacterium lactis* HN019, and *Lactocaseibacillus rhamnosus* HN001 significantly reduced the duration of fever in children with upper RTIs compared to the placebo group (Bettocchi et al., 2025). Among studied strains, *Lactocaseibacillus rhamnosus* CRL1505, originally isolated from goat milk, has shown immunomodulatory properties, particularly in enhancing respiratory immunity in pediatric populations (Chiba et al., 2013; Salva et al., 2010). A study involving preschool

* Corresponding author.

E-mail address: daniela.bassi@unicatt.it (D. Bassi).

<https://doi.org/10.1016/j.fbio.2025.108139>

Received 15 October 2025; Received in revised form 2 December 2025; Accepted 18 December 2025

Available online 18 December 2025

2212-4292/© 2025 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

children showed that CRL1505 supplementation reduced the frequency of upper RTIs and the need for antibiotic therapy (Kitazawa & Villena, 2014).

To confer health benefits to the host, it is widely accepted that probiotic formulations must contain a minimum concentration of 10^6 – 10^7 CFU per gram or milliliter of viable cells at the time of consumption. However, their viability can be compromised by various stressors during food processing, storage, and gastrointestinal transit (Fiocco et al., 2020). To address this challenge, delivery systems have been developed in order to encapsulate and protect bacteria from the adverse conditions that they may face (Gao et al., 2022). Albeit the complexity of the equipment and the high investment and maintenance costs associated with these protection methods, disadvantages are still present that limit their adoption (Rajam & Subramanian, 2022).

In the last years, chocolate has emerged as a promising alternative matrix for probiotic delivery, offering natural protection against gastric acidity and bile salts while maintaining probiotic viability (Muhammad et al., 2021; Roobab et al., 2020). Camelo-Silva et al. (2024) demonstrated that white chocolate enriched with *L. rhamnosus* GG co-encapsulated with beet residue extract maintained probiotic viability for 120 days at 4 °C and ensured survival through the gastrointestinal transit. Other studies have investigated the fortification of dark chocolate and confirmed its potential as an effective vehicle for the delivery of probiotic strains and other bioactive compounds (Faccinotto-Beltrán, Gómez-Fernández, Santacruz, & Jacobo-Velázquez, 2021; Samanta et al., 2022). Additionally, chocolate is a rich source of antioxidants, such as flavonoids (Faccinotto-Beltrán, Gómez-Fernández, Santacruz, & Jacobo-Velázquez, 2021), which have been associated with protective effects against cardiovascular diseases and cancer (Succi et al., 2017). Despite concerns over its fat and sugar content, chocolate fortification with functional ingredients may enhance health benefits of this widely consumed food (Hossain et al., 2021; Li & Wang, 2023; Singh et al., 2024).

Cinnamon, a spice derived from the bark of the cinnamon tree (Arya et al., 2022), is rich in bioactive compounds such as cinnamaldehyde, cinnamyl alcohol, cinnamic acid, and cinnamate, which exhibit antioxidant, anti-inflammatory, and antibacterial properties (Błaszczuk et al., 2021; Talgerd et al., 2023; Valdivieso-Ugarte et al., 2021). Recent investigations have also shown that cinnamon extract can enhance the antioxidant capacity of cocoa (Muhammad et al., 2017). Moreover, cinnamaldehyde and cinnamon-derived polyphenols have been reported to exert antimicrobial effects against respiratory pathogens such as *Streptococcus pneumoniae* and *Haemophilus influenzae* (Li et al., 2020; Qi et al., 2021; Ranasinghe et al., 2013; Ács et al., 2018). However, while the integration of cinnamon may augment the functional profile of probiotic-enriched chocolate products, its known antimicrobial activity necessitates careful evaluation. Among foodborne pathogens and spoilage microorganisms, cinnamon has demonstrated antibacterial activity against both gram-positive and gram-negative bacteria (Lucas-González et al., 2023). Its antibacterial mechanism is associated with disruptions of the cell membrane structure and lipid composition, inhibition of ATPase activity, interference with cell division, alteration of membrane porin function, and suppression of bacterial motility and biofilm formation, as well as an anti-quorum sensing effect (Vasconcelos et al., 2018). The antimicrobial activity of cinnamon against pathogenic microorganisms is highly desirable; however, its effects on probiotics and starter cultures are less favorable. Mengue et al. (2012) evaluated the impact of cinnamon essential oil on the starter culture and the probiotic strain *L. rhamnosus* ATCC 9595 in yogurt, observing a reduction in viable cell counts. Furthermore, De Giani et al. (2022) investigated the potential of cinnamon bark extract as a prebiotic. *L. rhamnosus* showed reduced growth in the presence of cinnamon, but, interestingly, its growth was promoted by the presence of previously digested cinnamon extract.

This study aimed to develop a novel milk chocolate praline enriched with the probiotic *L. rhamnosus* CRL1505 and to determine whether the

inclusion of cinnamon adversely affects probiotic viability. Two hazelnut-filled praline variants were produced, containing the probiotic strain with or without cinnamon, and stored at room temperature for 120 days. Over the shelf-life period, the synergistic effects of cinnamon and the chocolate matrix on probiotic viability were studied, and the survival of the probiotic under simulated *in vitro* gastrointestinal conditions was also evaluated.

2. Materials and methods

2.1. Production of chocolate pralines enriched with *L. rhamnosus* CRL1505 and cinnamon

Chocolate pralines were produced at the pilot plant of FGA Chocolate confectionery & Consultancy S.r.l. (Novi Ligure, Italy). The cocoa beans used in their production were imported from Peru and consisted of Criollo, Trinitario, and Forastero varieties.

A total of 25 kg of dried cocoa beans were stored at a temperature of 14 °C and a relative humidity of 70–75 %, to maintain a moisture content of 8 %. The beans were then roasted at 170 °C for 20 min using a roaster. Successively, the beans were ground in two phases. Initially, cocoa nibs were separated using a cocoa mill, leaving 2 % of the skin intact. Subsequently, pre-grinding with cylinders reduced the nibs' granulometry. The refining process, carried out using a ball mill, transformed the nibs into cocoa liquor by reducing particle size to less than 20 µm. Then, the cocoa liquor was transferred to the conche, where it underwent conching at 70 °C for 12 h.

In order to produce 6 kg of milk chocolate, a specific blend of ingredients was used (Table 1), including 0.72 kg of cocoa liquor, 1.44 kg of cocoa butter, 0.66 kg of milk powder, 1.11 kg of sucrose, 0.84 kg of whey proteins, 1.2 kg of inulin, 0.024 kg of lecithin, and 0.006 kg of vanillin. These ingredients were mixed in a ball mill for 20 min at 40 °C.

Two distinct praline formulations were prepared to assess the effect of cinnamon on probiotic viability: one without cinnamon (CRL) and one with cinnamon (CAN). For both versions, 1.5 kg of milk chocolate was mixed in the ball mill with 0.045 kg of lyophilized *L. rhamnosus* CRL1505 (Sacco System, Cadorago, Italy) for 5 min at 40 °C. This probiotic amount was selected to achieve an initial inoculum of approximately 8 log CFU/g in the pralines. For the CAN formulation, an additional 0.0524 kg (3.4 % w/w) of cinnamon powder from *Cinnamomum cassia* (Ubena alimentari S.r.l., Milan, Italy) was incorporated.

The tempered chocolate was poured into cubic molds and shaken to remove air bubbles, before being inverted to create hollow shells. The shells were cooled at 4 °C for 15 min. Subsequently, 5 g of hazelnut paste (EuroCompany S.r.l., Godo, Italy) was added to each shell, followed by an additional cooling step at 4 °C for 10 min. The pralines, consisting of 5 g of chocolate for the shell and 5 g of hazelnut paste, were then sealed with a final layer of chocolate and cooled at 4 °C for 20 min. Finally, they were demolded, wrapped in plastic, and stored at 25 °C for 120 days.

Table 1
List of ingredients utilized for the preparation of praline variants.

Ingredient	Concentration in CAN (%)	Concentration in CRL (%)
Cocoa liquor	11.2	11.6
Cocoa butter	22.5	23.2
Milk powder	10.3	10.6
Whey proteins	13.0	13.5
Inulin	18.7	19.4
Sucrose	17.3	17.9
Lecithin	0.4	0.4
Vanillin	0.1	0.1
Probiotic	2.8	2.9
Hazelnut paste	0.3	0.3
Cinnamon powder	3.4	0

2.2. Physicochemical characterization of chocolate pralines

The water activity (a_w) of each product was measured every 30 days over the 120-day shelf life (0, 30, 60, 90, and 120 days). To determine a_w , the samples were crushed with a mortar and pestle, placed in a crucible, and then analyzed in the AQUALAB 4 TE dew-point water activity meter (METER Group, Inc. USA, Pullman, WA, USA) at 25 °C.

The pH of the pralines was measured every 30 days using the edge® blu pH meter (Hanna Instruments Inc., Woonsocket, RI, USA). For each measurement, 5 g of praline sample was first crushed using a mortar and pestle and then diluted 1:10 in deionized water (Succi et al., 2017).

2.3. Viability of probiotic bacteria and microbiological quality during chocolate storage

A total of 10 g of each sample was homogenized in a BagMixer stomacher (Interscience, Saint-Nom-la-Bretèche, France) with 90 mL of Mitsuoka buffer (0.45 % Sodium phosphate dibasic dodecahydrate (Carlo Erba, Cornaredo, Italy), 0.6 % Potassium phosphate monobasic (Carlo Erba, Cornaredo, Italy), 0.05 % L-cysteine hydrochloride monohydrate (Merck KGaA, Darmstadt, Germany), 0.05 % Tween 80 (Merck KGaA, Darmstadt, Germany)). Decimal dilutions were obtained and plated onto De Man, Rogosa and Sharpe (MRS) Agar (Oxoid, Basingstoke, UK). Plates were incubated under anaerobic conditions (Anaerocult® A gas packs, Merck KGaA, Darmstadt, Germany) at 37 °C for 48 h. The viability of the probiotic was expressed as log CFU/g. The analyses were performed in triplicate at intervals of 30 days over a 120 days period.

Moreover, at the beginning (T0), and after 120 days (T4) samples were processed as described above to evaluate the count of molds, yeasts and total Enterobacteriaceae. In particular, molds and yeasts were cultivated on Rose Bengal (RB) Agar (Oxoid, Basingstoke, UK), supplemented with 0.05 g/L chloramphenicol (Merck KGaA, Darmstadt, Germany). Plates were incubated at 30 °C for 4 days. Enterobacteriaceae were grown on Violet Red Bile Glucose (VRBGA) Agar (Oxoid, Basingstoke, UK) and incubated at 37 °C for 48 h. The viability of molds, yeasts and total Enterobacteriaceae was expressed as log CFU/g. Analyses were performed in triplicate.

2.4. Evaluation of probiotic survival under in vitro digestion model

In order to assess the stability of *L. rhamnosus* CRL1505 in chocolate pralines during transit through the gastrointestinal tract, the standardized INFOGEST *in vitro* human digestion static protocol was applied, as described by Brodkorb et al. (2019). The method involves three sequential digestion phases: oral (2 min, 37 °C, pH 7.0), gastric (120 min, 37 °C, pH 3.0), and intestinal (120 min, 37 °C, pH 7.0). The enzyme concentrations and digestion conditions were standardized according to the guidelines provided by Minekus et al. (2014) and Brodkorb et al. (2019).

To simulate the chewing process, the pralines were manually crushed using a mortar. For each digestion, 5 g of praline were used, and 1 mL aliquots were collected after each digestion phase for microbiological analysis. These aliquots were then plated on MRS Agar to evaluate the viability of *L. rhamnosus* CRL1505. The analysis was conducted immediately after the production, and after 120 days, with each test performed in triplicates.

2.5. Statistical analysis

For each set of triplicates, the mean, standard deviation (SD), and variance were calculated. The Shapiro-Wilk test in Python (v3.12) was used to assess normality, while the Levene test was performed to evaluate the homogeneity of variance. A two-factor ANOVA with replication followed by Tukey's post-hoc test was conducted to statistically assess the effect of cinnamon and time on pH, water activity (a_w) and probiotic

viability using R (v4.4.3). Additionally, a two-factor ANOVA with Tukey's post-hoc test was performed on the digested sample data.

3. Results and discussion

The incorporation of probiotics into chocolate products has garnered significant interest in recent years (Faccinnetto-Beltrán, Gómez-Fernández, Santacruz, & Jacobo-Velázquez, 2021). Previous evidence demonstrated that probiotics, belonging to different species, maintained viability and, therefore, the effectiveness in delivering health-promoting properties in various types of chocolate products (Marcial-Coba et al., 2019). However, the incorporation of probiotics into this matrix presents some challenges. For instance, the conching temperature of chocolate typically ranges from 60 to 70 °C, which is critical to maintaining high probiotic viability (Zyzelewicz et al., 2012). Therefore, to prevent a significant reduction in probiotic concentration, the strains were added after the conching step, at a temperature of 40 °C.

The combination of chocolate with functional ingredients, such as cinnamon, inulin and hazelnut, is expected to potentially influence the probiotic behavior in the food matrix together with a functional effect on human health. Preclinical and clinical studies have demonstrated that cinnamon exhibits a range of pharmacological properties, including antioxidant, anti-inflammatory, and immunomodulatory effects (Gu et al., 2025). However, in addition to the health benefits, there is evidence that cinnamon may also have adverse effects, such as hepatotoxicity, carcinogenicity, and dermatitis (Gu et al., 2022). These side effects can be associated with the content of coumarin (Woehrlin et al., 2010). The tolerable daily intake (TDI) for cinnamon in Europe according to EFSA previous assessment has been set at 0.1 mg per kg of body weight (Gu et al., 2022), therefore, particular attention should be paid when considering cinnamon intake in children (European Food Safety Authority (EFSA), 2008). Assuming an average body weight of 30–35 kg for a school-aged child, the safe daily dose is 3–3.5 mg. In our praline, cinnamon was added at a concentration of 3.4 %, corresponding to 0.17 mg per praline, which highly remains within a safe range and does not pose a health risk for children.

Inulin was employed as a natural sweetener due to its dual function as a sweetening agent and prebiotic fiber. Its inclusion in the chocolate matrix not only contributes to lowering the content of simple sugars, but also provides a favorable substrate for the survival of probiotic strains (Toker et al., 2017).

Hazelnuts are a nutrient-rich food that provide significant amounts of vitamin E, B-group vitamins, magnesium, zinc, and essential fatty acids (Lai et al., 2021; Talebi et al., 2023). The total dietary fiber content of hazelnuts has been reported to be approximately 17.8 % (Tunçil, 2020). This fibers exhibit prebiotic potential by modulating the growth of beneficial microorganisms in the colon (Lin et al., 2024).

In this study, we developed a new functional chocolate-based product intended for children, specifically designed to help combat seasonal respiratory diseases. Accordingly, *L. rhamnosus* CRL1505 and cinnamon were incorporated into the praline formulations, and the effect of the spice on probiotic viability during storage and simulated digestion was evaluated. We acknowledge that chocolate is not generally regarded as a healthy food for children. However, the product developed in this study, formulated with carefully selected ingredients, is intended to serve as a palatable supplement for occasional consumption.

3.1. Physicochemical characterization of chocolate pralines

Among the various physicochemical indicators used to evaluate food quality of pralines along the shelf life, pH and water activity (a_w) were selected. As illustrated in Fig. 1, the a_w values in CRL praline initially increased from 0.371 ± 0.001 to 0.399 ± 0.003 during the first 30 days, then returned to 0.368 ± 0.004 by 90 days. Subsequently, a gradual increase was observed, reaching a peak of 0.418 ± 0.008 . In the CAN praline, a similar trend was observed, ending at a final value of $0.422 \pm$

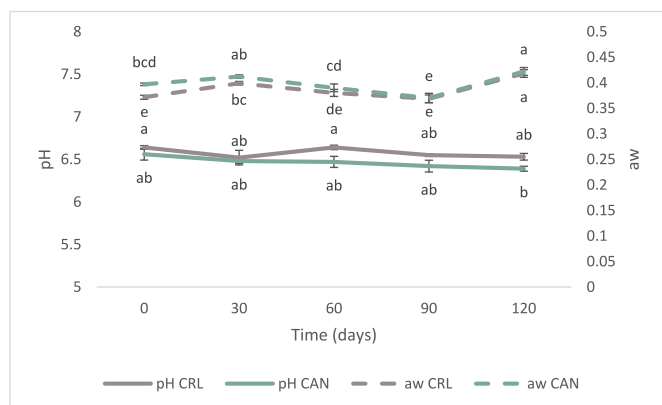


Fig. 1. pH and water activity (a_w) over the 120 days shelf life in praline formulations with (CAN) and without (CRL) cinnamon. The values of pH and a_w are expressed as mean \pm standard deviation of three independent experiments. Different letters (^{a-d}) indicate significant differences according to two-way ANOVA and Tukey's post hoc test ($p < 0.05$).

0.004. Both the samples showed some fluctuations over time, but ultimately maintained a not statistically different a_w value at the end of the storage period. These values align with previous findings (Silva et al., 2017; Toker et al., 2017) and can be attributed to the complexity of the chocolate matrix, which includes a high fat content and various other ingredients. Notably, a_w values below 0.6 help ensure the microbiological safety of the product (Silva et al., 2017).

The pH remained stable throughout the storage period in both formulations (Fig. 1). In the praline without cinnamon, it ranged between 6.64 ± 0.08 and 6.53 ± 0.01 , while in the cinnamon-containing variant, it was slightly lower, fluctuating between 6.56 ± 0.09 and 6.39 ± 0.01 . These values were generally higher than those reported for other chocolate formulations (Cielecka-Piontek et al., 2020; Silva et al., 2017), which may be attributed to the presence of milk in the chocolate recipe.

3.2. Probiotic viability and microbiological quality during chocolate storage

Probiotic viability was monitored every 30 days, while microbiological quality was evaluated at the beginning of storage, and after 120 days.

The stability of *L. rhamnosus* CRL1505 in milk chocolate remained relatively high during the shelf life. As shown in Fig. 2, a statistically significant reduction of 0.43 log CFU/g in microbial load was observed

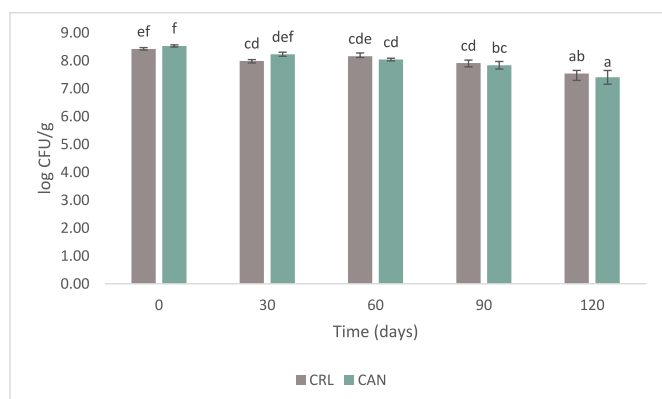


Fig. 2. Probiotic viability (log CFU/g) in chocolate pralines with (CAN) and without (CRL) cinnamon over the 120 days shelf life. The results are expressed as mean value ($n = 3$ biological replicates) \pm standard deviation. Different letters (^{a-f}) denote significant differences between samples, as determined by two-way ANOVA coupled with a Tukey's post hoc test ($p < 0.05$).

in the CRL formulation after 30 days of storage. Following this initial decline, the cell count remained stable until day 90, with no further significant changes. A second statistically significant decrease occurred after 120 days. In contrast, the CAN formulation did not exhibit a significant reduction in probiotic counts during the first 30 days of storage. A notable decrease occurred at day 60, followed by a period of stability until day 90. Over the final 30 days of storage, the CAN sample experienced another statistically significant reduction.

After 120 days of storage at room temperature, a total reduction of 0.88 log CFU/g was observed in the praline without cinnamon, while the praline containing the spice exhibited a decrease of 0.90 log CFU/g.

Hossain et al. (2021) have reported that free cells of *L. rhamnosus* LGG in chocolate stored under similar conditions with an initial cell load of 12 log CFU/g dropped below 2 log CFU/g after 120 days, whereas encapsulation was necessary to maintain viability at approximately 7 log CFU/g. In comparison, *L. rhamnosus* CRL1505 in our chocolate matrix reached 7.54 ± 0.11 log CFU/g (CRL) and 7.40 ± 0.25 log CFU/g (CAN), starting from initial loads of 8.42 ± 0.05 and 8.53 ± 0.04 log CFU/g, respectively. These values highlight the superior resilience of CRL1505 in our chocolate formulation, achieved without the need for encapsulation.

Previous studies by Lalicic-Petronijevic et al. (2015) and Hossain et al. (2022) also demonstrated that storage temperature significantly influences probiotic viability in chocolate, with greater reductions observed at 25 °C compared to refrigerated conditions. However, *L. rhamnosus* CRL1505 in the present study exhibited excellent stability during storage at ambient temperature. These findings suggest that CRL1505 is an ideal candidate for the development of functional chocolate products, offering a cost-effective solution for maintaining probiotic functionality without the need for cold storage.

In addition to its well-documented antioxidant properties, cinnamon has been reported to possess significant antimicrobial activity, predominantly attributed to its principal active component, cinnamaldehyde (Shu et al., 2024). This antimicrobial potential may pose challenges in maintaining the viability of probiotic microorganisms in fortified food products. Fig. 2 presents the variation in bacterial cell counts in CRL and CAN pralines, formulated with and without the addition of cinnamon. Statistical analysis revealed comparable viability between the two formulations during the 120 days of storage. Throughout the storage period, no significant differences were observed between the two variants at any sampling time, indicating that the addition of 3.4 % (w/w) cinnamon did not adversely affect the viability of CRL1505 in the chocolate matrix.

Previous research has demonstrated that chocolate matrices provide superior protection to probiotics under both storage and gastrointestinal conditions (Hossain et al., 2022; Muhammad et al., 2021; Silva et al., 2017). Furthermore, the high fat content in certain foods can sequester hydrophobic components, thereby limiting their direct contact with microbial cells (Mengue Feniman Moritz et al., 2015; Wang et al., 2023). Considering that chocolate presents a complex matrix rich in lipids and polyphenols (Samanta et al., 2022), it is reasonable that its physicochemical properties help mitigate the antimicrobial activity of cinnamon, thus promoting the stability of CRL1505 over time. Supporting this hypothesis, Singh and Gaur (2025) reported that the inclusion of additional ingredients such as cinnamon in chocolate formulations contributed providing an improved protective environment for probiotics, resulting in only modest reductions in cell viability.

These results are particularly relevant for the development of functional chocolate products, demonstrating that cinnamon can be incorporated as a natural flavoring agent without substantially compromising probiotic stability.

Microbiological quality was also evaluated in chocolate pralines at 0 and 120 days. Molds, yeasts and Enterobacteriaceae were enumerated, and in both formulations, their levels remained below the European Union's safety threshold of 100 CFU/g (European Union, 2005, 2017) throughout the storage period. These findings confirm that both product

variants are microbiologically safe for human consumption.

3.3. Impact of *in vitro* digestion on probiotic viability in chocolate praline during the shelf life

Food matrices can enhance the survival of probiotics by providing additional protection during their transit through the gastrointestinal tract (Silva et al., 2017). In this study, the standardized INFOGEST *in vitro* human digestion static model was employed to evaluate the survival of *L. rhamnosus* CRL1505 in the two praline formulations (CAN and CRL) at two time points throughout the shelf life: 0 (T0), and 120 (T4) days. Probiotic survival was expressed as the percentage of viable cells recovered after each digestive phase. Although previous studies have already demonstrated the potential of chocolate as a protective delivery vehicle for probiotics (Cielecka-Piontek et al., 2020; Silva et al., 2017), limited data are available on how this protective capacity may change over time during product storage.

At T0, both formulations showed similar behavior, with CRL1505 maintaining high viability (>77 %) across all digestive phases (Fig. 3). Notably, both variants exhibited lower survival rates following the oral phase compared to the gastric and intestinal phases. This reduced survival may be attributed to methodological limitations, particularly those related to sample processing. The oral phase of the *in vitro* digestion, lasting only 2 min and conducted at neutral pH, may not have been sufficient to achieve complete solubilization of the chocolate matrix, thereby limiting the release of probiotic cells into the simulated salivary fluid. Across all digestive phases, the CRL formulation showed slightly higher probiotic counts compared to CAN, with values of 6.96 and 6.60 log CFU/g after the oral phase, 7.89 and 7.47 log CFU/g following the gastric phase, and 8.01 and 6.92 log CFU/g after the intestinal phase, respectively.

Singh and Gaur (2025), who developed a probiotic-enriched chocolate, reported that the viability of *L. rhamnosus* GG decreased from 8.62 log CFU/g to 5.78 log CFU/g, following simulated gastrointestinal digestion. An even greater limitation was described by Cielecka-Piontek et al. (2020), who observed 4- and 3-log reductions for *L. rhamnosus* GG and *Lactocaseibacillus paracasei* F19 in dark chocolate after the gastric and intestinal phases, respectively. Hossain et al. (2022) reported a 7-log reduction for non-encapsulated and a 4-log reduction for encapsulated *Lactobacillus delbrueckii* subsp. *bulgaricus* in chocolate after gastric digestion. By contrast, CRL1505 in the current study demonstrated superior stability, with only a 1-log reduction observed after each digestive stage.

After 120 days of storage, *L. rhamnosus* CRL1505 continued to exhibit excellent survival in both praline formulations (Fig. 3). The trend observed at T0 was maintained over time, with slightly reduced survival following the oral phase compared to the gastric and intestinal phases. Notably, the probiotic demonstrated high resistance to simulated gastric and intestinal digestion, with survival rates consistently above 86 % at T4. Furthermore, no significant differences in the CRL1505 survival were observed between the two formulations after the gastric and

intestinal phases.

To date, the impact of storage on the survival of probiotics in chocolate during simulated digestion has been scarcely addressed. Hossain et al. (2022), who reported substantial viability losses for *L. delbrueckii* subsp. *bulgaricus* in chocolate after just one day of storage following simulated digestion, observed similar survival trends after 90 days, suggesting that shelf life had a limited impact on the strain's digestive stability. In the present study, *L. rhamnosus* CRL1505 consistently exhibited only a 1 log CFU/g reduction across all digestive phases and storage times (T0, T4), underscoring its stability and strong potential for application in probiotic chocolate formulations.

4. Conclusions

The growing demand for functional foods has driven innovation in probiotic-enriched products, such as chocolate. In this study, two functional chocolate pralines fortified with *L. rhamnosus* CRL1505 were successfully developed, one of which was further enriched with cinnamon powder (3.4 % w/w), a natural antioxidant and antimicrobial agent. The incorporation of cinnamon did not alter the physicochemical properties of the chocolate, nor did it drastically impair probiotic viability. Notably, both formulations maintained high probiotic counts after 120 days of storage, with final concentrations of 7.54 ± 0.11 log CFU/g (without cinnamon) and 7.40 ± 0.25 log CFU/g (with cinnamon). Although a slight decrease in viability was observed in both formulations after 120 days, no significant differences were found between the two samples at any sampling time during the storage period. Moreover, *in vitro* gastrointestinal simulation confirmed robust survival of CRL1505 in both formulations, even after extended storage, highlighting the protective role of the chocolate matrix.

These findings demonstrate that chocolate is an effective carrier for *L. rhamnosus* CRL1505, offering protection during storage and digestion, even in the presence of potential antimicrobials. Importantly, this study provides evidence that cinnamon can be incorporated into probiotic chocolate products supplemented with *L. rhamnosus* strains without critically compromising bacterial viability. This supports the development of novel confectionery products that combine probiotics and natural flavors. Although chocolate is not generally regarded as a healthy food choice for children, the product developed in this study was formulated as a palatable supplement intended for occasional consumption. Inulin was incorporated into the recipe to reduce the content of simple sugars and to confer an additional prebiotic function, while hazelnut paste was included to enhance the lipid profile of the praline through its naturally high content of unsaturated fatty acids.

Future studies may focus on optimizing cinnamon concentrations, evaluating sensory acceptance, and improving the nutritional profile of the product to enhance its commercial applicability.

CRediT authorship contribution statement

Marianna Bozzetti: Writing – review & editing, Writing – original

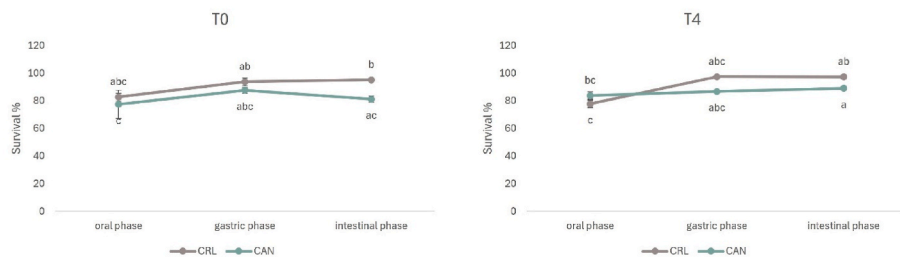


Fig. 3. Survival of *L. rhamnosus* CRL1505 in the chocolate formulations (CAN and CRL) under *in vitro* simulated gastrointestinal digestion after 0 (T0), and 120 (T4) days of storage. Data are expressed as mean survival percentage ($n = 3$ biological replicates) \pm standard deviation. Different letters (^{a-c}) denote significant differences between samples, as determined by two-way ANOVA coupled with Tukey's post hoc test ($p < 0.05$).

draft, Formal analysis, Data curation. **Eleonora Galli**: Writing – original draft, Formal analysis, Data curation. **Claudia Cortimiglia**: Writing – review & editing, Funding acquisition, Data curation. **Ernesto Carrega**: Methodology, Conceptualization. **Mariasole Cervini**: Formal analysis. **Paolo Cernuschi**: Conceptualization. **Daniela Bassi**: Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The other 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.

Acknowledgements

This study was supported by the PhD in Agro-Food System (Agri-system) and by Portus project funded by Romeo and Enrica Invernizzi Foundation.

This research was also funded by the European Union – NextGenerationEU, Mission 4 Component 2 Investment 1.3, Project code PE00000003.

The *L. rhamnosus* CRL1505 strain used in this study was kindly provided by Sacco System (Cadorago, Italy).

Data availability

Data will be made available on request.

References

- Ács, K., Balázs, V. L., Kocsis, B., Bencsik, T., Böszörményi, A., & Horváth, G. (2018). Antibacterial activity evaluation of selected essential oils in liquid and vapor phase on respiratory tract pathogens. *BMC Complementary and Alternative Medicine*, 18(1), 1–9. <https://doi.org/10.1186/S12906-018-2291-9/TABLES/6>
- Arya, P., Kumari, N., Ahmad Wani, S., & Kumar, P. (2022). Cinnamon as a potential nutraceutical and functional food ingredient. In *Herbs, spices and their roles in nutraceuticals and functional foods* (pp. 133–148). Elsevier. <https://doi.org/10.1016/B978-0-323-90794-1.00001-6>
- Bettocchi, S., Comotti, A., Elli, M., De Cosmi, V., Berti, C., Alberti, I., Mazzocchi, A., Rosazza, C., Agostoni, C., & Milani, G. P. (2025). Probiotics and fever duration in children with upper respiratory tract infections: A randomized clinical trial. *JAMA Network Open*, 8(3), Article e250669. <https://doi.org/10.1001/JAMANETWORKOPEN.2025.0669>
- Błaszczak, N., Rosiak, A., & Kałużna-Czaplińska, J. (2021). The potential role of cinnamon in human health. *Forests*, 12(5). <https://doi.org/10.3390/f12050648>. MDPI AG.
- Brodtkorb, A., Egger, L., Alminger, M., Alvito, P., Assunção, R., Ballance, S., Bohn, T., Bourlieu-Lacanal, C., Boutrou, R., Carrière, F., Clemente, A., Corredig, M., Dupont, D., Dufour, C., Edwards, C., Golding, M., Karakaya, S., Kirkhus, B., Le Feunteun, S., ... Recio, I. (2019). INFOGEST static in vitro simulation of gastrointestinal food digestion. *Nature Protocols*, 14(4), 991–1014. <https://doi.org/10.1038/s41596-018-0119-1>
- Camelo-Silva, C., Mota e Souza, B., Vicente, R., Arend, G. D., Sanches, M. A. R., Barreto, P. L. M., Ambrosi, A., Verruck, S., & Di Luccio, M. (2024). Polyfunctional sugar-free white chocolate fortified with *Lactobacillus rhamnosus* GG co-encapsulated with beet residue extract (beta vulgaris L.). *Food Research International*, 179. <https://doi.org/10.1016/j.foodres.2024.114016>
- Chiba, E., Tomosada, Y., Vizoso-Pinto, M. G., Salva, S., Takahashi, T., Tsukida, K., Kitazawa, H., Alvarez, S., & Villena, J. (2013). Immunobiotic *Lactobacillus rhamnosus* improves resistance of infant mice against respiratory syncytial virus infection. *International Immunopharmacology*, 17(2), 373–382. <https://doi.org/10.1016/j.intimp.2013.06.024>
- Cielecka-Piontek, J., Dziedzinski, M., Szczepaniak, O., Kobus-Cisowska, J., Telichowska, A., & Szymanowska, D. (2020). Survival of commercial probiotic strains and their effect on dark chocolate synbiotic snack with raspberry content during the storage and after simulated digestion. *Electronic Journal of Biotechnology*, 48, 62–71. <https://doi.org/10.1016/J.EJBT.2020.09.005>
- De Giani, A., Pagliari, S., Zampolli, J., Forcella, M., Fusi, P., Bruni, I., Campone, L., & Di Genarro, P. (2022). Characterization of the biological activities of a new polyphenol-rich extract from cinnamon bark on a probiotic consortium and its action after enzymatic and microbial fermentation on colorectal cell lines. *Foods*, 11(20). <https://doi.org/10.3390/foods11203202>
- European Food Safety Authority (EFSA). (2008). Coumarin in flavourings and other food ingredients with flavouring properties - scientific opinion of the panel on food additives, flavourings, processing aids and materials in contact with food (AFC). *EFSA Journal*, 6(10). <https://doi.org/10.2903/j.efsa.2008.793>
- European Union. (2005). Regulation (EC) no 2073/2005 of 15 November 2005 on microbiological criteria for foodstuffs. *Official Journal of the European Union*, L 338. <https://eur-lex.europa.eu/legal-content/IT/TXT/?uri=CELEX%3A32005R2073>
- European Union. (2017). Commission implementing regulation (EU) 2017/2470 of 20 December 2017 establishing the union list of novel foods in accordance with regulation (EU) 2015/2283 of the European Parliament and of the council on novel foods. *Official Journal of the European Union*, L 351. <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32017R2470>
- Faccinnetto-Beltrán, P., Gómez-Fernández, A. R., Orozco-Sánchez, N. E., Pérez-Carrillo, E., Marín-Obispo, L. M., Hernández-Brenes, C., Santacruz, A., & Jacobo-Velázquez, D. A. (2021). Physicochemical properties and sensory acceptability of a next-generation functional chocolate added with omega-3 polyunsaturated fatty acids and probiotics. *Foods*, 10(2). <https://doi.org/10.3390/foods10020333>
- Faccinnetto-Beltrán, P., Gómez-Fernández, A. R., Santacruz, A., & Jacobo-Velázquez, D. A. (2021). Chocolate as carrier to deliver bioactive ingredients: Current advances and future perspectives. *Foods*, 10(9), 2065. <https://doi.org/10.3390/FOODS10092065>
- Fiocco, D., Longo, A., Arena, M. P., Russo, P., Spano, G., & Capozzi, V. (2020). How probiotics face food stress: They get by with a little help. *Critical Reviews in Food Science and Nutrition*, 60(9), 1552–1580. <https://doi.org/10.1080/10408398.2019.1580673>. Taylor and Francis Inc.
- Gao, H., Ma, L., Sun, W., McClements, D. J., Cheng, C., Zeng, H., Zou, L., & Liu, W. (2022). Impact of encapsulation of probiotics in oil-in-water high internal phase emulsions on their thermostability and gastrointestinal survival. *Food Hydrocolloids*, 126. <https://doi.org/10.1016/j.foodhyd.2021.107478>
- Gou, H., Zhong, L., Wei, Q., & Fan, Y. (2025). The effects of cinnamon on patients with metabolic diseases: An umbrella review of meta-analyses of randomized controlled trials. *Frontiers in Nutrition*, 12, Article 1683477. <https://doi.org/10.3389/FNUT.2025.1683477>
- Gu, D. T., Tung, T. H., Jiesibieke, Z. L., Chien, C. W., & Liu, W. Y. (2022). Safety of cinnamon: An umbrella review of meta-analyses and systematic reviews of randomized clinical trials. *Frontiers in Pharmacology*, 12, Article 790901. <https://doi.org/10.3389/FPHAR.2021.790901>
- Hossain, M. N., Ranadheera, C. S., Fang, Z., Hutchinson, G., & Ajlouni, S. (2021). Protecting the viability of encapsulated *Lactobacillus rhamnosus* LGG using chocolate as a carrier. *Emirates Journal of Food and Agriculture*, 33(8), 647–656. <https://doi.org/10.9755/ejfa.2021.v33.i8.2740>
- Hossain, M. N., Senaka Ranadheera, C., Fang, Z., Masum, A. K. M., & Ajlouni, S. (2022). Viability of *Lactobacillus delbrueckii* in chocolates during storage and in-vitro bioaccessibility of polyphenols and SCFAs. *Current Research in Food Science*, 5, 1266–1275. <https://doi.org/10.1016/J.CRFS.2022.08.001>
- Kitazawa, H., & Villena, J. (2014). Modulation of respiratory TLR3-anti-viral response by probiotic microorganisms: Lessons learned from *Lactobacillus rhamnosus* CRL1505. *Frontiers in Immunology*, 5(MAY), Article 71179. <https://doi.org/10.3389/FIMMU.2014.00201/BIBTEX>
- Lai, J. S., Cai, S., Feng, L., Shek, L. P., Yap, F., Tan, K. H., Chong, Y. S., Godfrey, K. M., Meaney, M. J., Rifkin-Graboi, A., Broekman, B. F. P., & Chong, M. F. F. (2021). Associations of maternal zinc and magnesium with offspring learning abilities and cognitive development at 4 years in GUSTO. *Nutritional Neuroscience*, 24(6), 467–476. <https://doi.org/10.1080/1028415X.2019.1643624>
- Lallicic-Petronijevic, J., Popov-Raljić, J., Obradović, D., Radulović, Z., Paunović, D., Petrušić, M., & Pezo, L. (2015). Viability of probiotic strains *Lactobacillus acidophilus* NCFM® and *Bifidobacterium lactis* HN019 and their impact on sensory and rheological properties of milk and dark chocolates during storage for 180 days. *Journal of Functional Foods*, 15, 541–550. <https://doi.org/10.1016/J.JFF.2015.03.046>
- Li, A. li, Ni, W. wei, Zhang, Q. min, Li, Y., Zhang, X., Wu, H. yan, Du, P., Hou, J. cai, & Zhang, Y. (2020). Effect of cinnamon essential oil on gut microbiota in the mouse model of dextran sodium sulfate-induced colitis. *Microbiology and Immunology*, 64(1), 23–32. <https://doi.org/10.1111/1348-0421.12749>. SUBPAGE.STRING:FULL.
- Li, X., & Wang, S. C. (2023). Upcycling flavanol-rich Chardonnay and Pinot noir grape thinned clusters as potentially functional food ingredients in cocoa-based products. *Food Science and Nutrition*, 11(6), 3497. <https://doi.org/10.1002/FNS3.3338>
- Lin, H., Li, J., Sun, M., Wang, X., Zhao, J., Zhang, W., Lv, G., Wang, Y., & Lin, Z. (2024). Effects of hazelnut soluble dietary fiber on lipid-lowering and gut microbiota in high-fat-diet-fed rats. *International Journal of Biological Macromolecules*, 256, Article 128538. <https://doi.org/10.1016/J.IJBIOMAC.2023.128538>
- Liu, S., Hu, P., Du, X., Zhou, T., & Pei, X. (2013). *Lactobacillus rhamnosus* GG supplementation for preventing respiratory infections in children: A meta-analysis of randomized, placebo-controlled trials. *Indian Pediatrics*, 50(4), 377–381. <https://doi.org/10.1007/S13312-013-0123-Z>
- Lucas-González, R., Yilmaz, B., Mousavi Khaneghah, A., Hano, C., Shariati, M. A., Bangar, S. P., Goksen, G., Dhama, K., & Lorenzo, J. M. (2023). Cinnamon: An antimicrobial ingredient for active packaging. *Food Packaging and Shelf Life*, 35, Article 101026. <https://doi.org/10.1016/J.FPSL.2023.101026>
- Marcial-Coba, M. S., Saaby, L., Knochel, S., & Nielsen, D. S. (2019). Dark chocolate as a stable carrier of microencapsulated *Akkermansia muciniphila* and *Lactobacillus casei*. *FEMS Microbiology Letters*, 366(2). <https://doi.org/10.1093/FEMSLE/FNY290>
- Mengue Feniman Moritz, C., Lúcia Mores Rall, V., Juri Saeki, M., & Fernandes Júnior, A. (2015). Assessment of antimicrobial activity of cinnamon (*Cinnamomum zeylanicum*) essential oil combined with EDTA and polyethylene glycol in yogurt (Vol. 1, pp. 99–104). <https://doi.org/10.4025/actascitecnol.v37i1.17325>
- Mengue, C., Moritz, F., Lúcia, V., Rall, M., Saeki, M. J., & Fernandes Júnior, A. (2012). Inhibitory effect of essential oils against *Lactobacillus rhamnosus* and starter culture in fermented milk during its shelf-life period. *Brazilian Journal of Microbiology*, 1147–1156. <https://doi.org/10.1590/s1517-838220120003000042>

- Minekus, M., Alvinger, M., Alvito, P., Ballance, S., Bohn, T., Bourliou, C., Carrière, F., Boutrou, R., Corredig, M., Dupont, D., Dufour, C., Egger, L., Golding, M., Karakaya, S., Kirkhus, B., Le Feunteun, S., Lesmes, U., Maclerzanka, A., MacKie, A., ... Brodkorb, A. (2014). A standardised static in vitro digestion method suitable for food-an international consensus. *Food & Function*, 5(6), 1113–1124. <https://doi.org/10.1039/c3fo60702j>
- Mordor Intelligence. (2025). Probiotic dietary supplement market size. <https://www.mordorintelligence.com/industry-reports/probiotic-dietary-supplement-market>.
- Muhammad, D. R. A., Praseptianga, D., Van de Walle, D., & Dewettinck, K. (2017). Interaction between natural antioxidants derived from cinnamon and cocoa in binary and complex mixtures. *Food Chemistry*, 231, 356–364. <https://doi.org/10.1016/j.foodchem.2017.03.128>
- Muhammad, D. R. A., Rahayu, E. S., & Fibri, D. L. N. (2021). Revisiting the development of probiotic-based functional chocolates. *Reviews in agricultural science*. <https://doi.org/10.7831/ras.9.0.233>
- Qi, L., Mao, H., Lu, X., Shi, T., & Wang, J. (2021). Cinnamaldehyde promotes the intestinal barrier functions and reshapes gut microbiome in early weaned rats. *Frontiers in Nutrition*, 8, Article 748503. <https://doi.org/10.3389/fnut.2021.748503>
- Rajam, R., & Subramanian, P. (2022). Encapsulation of probiotics: Past, present and future. *Beni-Suef University Journal of Basic and Applied Sciences*, 11(1). <https://doi.org/10.1186/s43088-022-00228-w>. Springer Science and Business Media Deutschland GmbH.
- Ranasinghe, P., Piger, S., Premakumara, G. S., Galappaththy, P., Constantine, G. R., & Katulanda, P. (2013). Medicinal properties of “true” cinnamon (*Cinnamomum zeylanicum*): A systematic review. *BMC Complementary and Alternative Medicine*, 13(1), 1–10. <https://doi.org/10.1186/1472-6882-13-275/TABLES/1>
- Roobab, U., Batoool, Z., Manzoor, M. F., Shabbir, M. A., Khan, M. R., & Aadil, R. M. (2020). Sources, formulations, advanced delivery and health benefits of probiotics. *Current Opinion in Food Science*, 32, 17–28. <https://doi.org/10.1016/j.cofs.2020.01.003>. Elsevier Ltd.
- Salva, S., Villena, J., & Alvarez, S. (2010). Immunomodulatory activity of *Lactobacillus rhamnosus* strains isolated from goat milk: Impact on intestinal and respiratory infections. *International Journal of Food Microbiology*, 141(1–2), 82–89. <https://doi.org/10.1016/j.ijfoodmicro.2010.03.013>
- Samanta, S., Sarkar, T., Chakraborty, R., Rebezov, M., Shariati, M. A., Thiruvengadam, M., & Rengasamy, K. R. R. (2022). Dark chocolate: An overview of its biological activity, processing, and fortification approaches. *Current Research in Food Science*, 5, 1916–1943. <https://doi.org/10.1016/j.crf.2022.10.017>. Elsevier B. V.
- Shu, C., Ge, L., Li, Z., Chen, B., Liao, S., Lu, L., Wu, Q., Jiang, X., An, Y., Wang, Z., & Qu, M. (2024). Antibacterial activity of cinnamon essential oil and its main component of cinnamaldehyde and the underlying mechanism. *Frontiers in Pharmacology*, 15, Article 1378434. <https://doi.org/10.3389/fphar.2024.1378434/FULL>
- Silva, M. P., Tulini, F. L., Marinho, J. F. U., Mazzocato, M. C., De Martinis, E. C. P., Luccas, V., & Favaro-Trindade, C. S. (2017). Semisweet chocolate as a vehicle for the probiotics *Lactobacillus acidophilus* LA3 and *Bifidobacterium animalis* subsp. *lactis* BLC1: Evaluation of chocolate stability and probiotic survival under in vitro simulated gastrointestinal conditions. *LWT*, 75, 640–647. <https://doi.org/10.1016/j.lwt.2016.10.025>
- Singh, S., & Gaur, S. (2025). Novel formulations of Cinnamon- and orange-flavored synbiotic corn chocolates with enhanced functional properties and probiotic survival rates. *ACS Food Science & Technology*. <https://doi.org/10.1021/acsfoodscitech.4c00741>
- Singh, P. K., Khedkar, R. D., & Chandra, S. (2024). Chocolate: An overview of functional potential and recent trends in fortification. *Brazilian Journal of Food Technology*, 27. <https://doi.org/10.1590/1981-6723.11823>. Instituto de Tecnologia de Alimentos - ITAL.
- Succi, M., Tremonte, P., Pannella, G., Tipaldi, L., Cozzolino, A., Coppola, R., & Sorrentino, E. (2017). Survival of commercial probiotic strains in dark chocolate with high cocoa and phenols content during the storage and in a static in vitro digestion model. *Journal of Functional Foods*, 35, 60–67. <https://doi.org/10.1016/j.jff.2017.05.019>
- Talebi, S., Khodaghali, F., Bahaeddin, Z., Dezfouli, M. A., Zeinaddini-Meymand, A., Kankam, S. B., Foolad, F., Alijaniha, F., Fatemeh, Piranghar, F., Fayazi, F., & Fayazi Piranghar, F. (2023). Does hazelnut consumption affect brain health and function against neurodegenerative diseases?. <https://doi.org/10.1080/1028415X.2023.2296164>.
- Talger, M., Jahromi, K. K., & Salehi, M. (2023). Effect of cinnamon on immune responses to an exhaustive exercise session in active males. *Journal of Sport Biosciences*, 15(2), 15–27. <https://doi.org/10.22059/jsb.2023.356437.1579>
- Tarahi, M., Tahmouzi, S., Kianiani, M. R., Ezzati, S., Hedayati, S., & Niakousari, M. (2024). Current innovations in the development of functional gummy candies. *Foods*, 13(1). <https://doi.org/10.3390/foods13010076>. Multidisciplinary Digital Publishing Institute (MDPI).
- Toker, O. S., Genc Polat, D., Gulfidan, O. G., Konar, N., Palabiyik, İ., Akcicek, A., Poyrazoglu, E. S., & Sagdic, O. (2017). Stability of lactic acid bacteria in synbiotic sugared and sugar-free milk chocolates. *International Journal of Food Properties*, 20, 1354–1365. <https://doi.org/10.1080/10942912.2017.1344990>
- Tunçil, Y. E. (2020). Dietary fibre profiles of Turkish Tombul hazelnut (*Corylus avellana* L.) and hazelnut skin. *Food Chemistry*, 316. <https://doi.org/10.1016/j.foodchem.2020.126338>
- Valdivieso-Ugarte, M., Plaza-Diaz, J., Gomez-Llorente, C., Lucas Gómez, E., Sabés-Alsina, M., & Gil, Á. (2021). In vitro examination of antibacterial and immunomodulatory activities of cinnamon, white thyme, and clove essential oils. *Journal of Functional Foods*, 81. <https://doi.org/10.1016/j.jff.2021.104436>
- Vasconcelos, N. G., Croda, J., & Simionatto, S. (2018). Antibacterial mechanisms of cinnamon and its constituents: A review. *Microbial Pathogenesis*, 120, 198–203. <https://doi.org/10.1016/j.micpath.2018.04.036>
- Villena, J., Chiba, E., Tomosada, Y., Salva, S., Marranzino, G., Kitazawa, H., & Alvarez, S. (2012). Orally administered *Lactobacillus rhamnosus* modulates the respiratory immune response triggered by the viral pathogen-associated molecular pattern poly (I:C). *BMC Immunology*, 13(1), 1–15. <https://doi.org/10.1186/1471-2172-13-53/FIGURES/9>
- Wang, L., Dekker, M., Heising, J., Zhao, L., & Fogliano, V. (2023). Food matrix design can influence the antimicrobial activity in the food systems: A narrative review. *Critical Reviews in Food Science and Nutrition*, 64(25), 8963–8989. <https://doi.org/10.1080/10408398.2023.2205937>. REQUESTEDJOURNAL:JOURNAL:BFSN20.
- Wang, Y., Li, X., Ge, T., Xiao, Y., Liao, Y., Cui, Y., Zhang, Y., Ho, W., Yu, G., & Zhang, T. (2016). Probiotics for prevention and treatment of respiratory tract infections in children: A systematic review and meta-analysis of randomized controlled trials. *Medicine (United States)*, 95(31). <https://doi.org/10.1097/MD.0000000000004509>
- Woehrlin, F., Fry, H., Abraham, K., & Preiss-Weigert, A. (2010). Quantification of flavoring constituents in cinnamon: High variation of coumarin in cassia bark from the German retail market and in authentic samples from Indonesia. *Journal of Agricultural and Food Chemistry*, 58(19), 10568–10575. https://doi.org/10.1021/JF102112P/SUPPL_FILE/JF102112P_SI_001.PDF
- Zyzelewicz, D., Motyl, I., Nebesny, E., Budryn, G., Krysiak, W., Rosicka-Kaczmarek, J., Libudzisz, Z., Zyzelewicz, D., Motyl, I., Nebesny, E., Budryn, G., Krysiak, W., Rosicka-Kaczmarek, J., & Libudzisz, Z. (2012). Probiotic confectionery products – Preparation and properties. *Probiotics*. <https://doi.org/10.5772/50047>