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REVIEW

Nonbovine milk and its products as sources of probiotics delivery: An overview of its viability, functionality and product quality characteristics

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Dairy products are the most predominant food carriers for probiotics, providing adequate therapeutic and functional benefits to the host when sufficient probiotics are maintained. Bovine milk currently dominates the global probiotic food market, but there is an increasing trend of applying nonbovine milk from other dairy animals as probiotic carrier food matrices as described in this review. Nonbovine dairy products can be considered suitable food matrices for probiotic delivery due to their excellent probiotic viability (mostly >log 7 cfu/mL or g) during shelf life, functional properties and product quality characteristics, being considered desirable and novel dairy products.

Keywords nonbovine milk, dairy, probiotic, goat milk, sheep milk, camel milk.

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A BRIEF INTRODUCTION TO PROBIOTICS

Current probiotic concepts were primarily observed in the early 1900s, and their descriptions and definitions evolved significantly during the last century. The most widely used definition for probiotics is recently orientated towards the 'live microorganisms which, when administered in adequate amounts, confer a health benefit on the host' (Hill *et al*. 2014). A sufficient intake of live probiotics (10^6–10^9 cfu/mL or g), also known as minimum therapeutic level can promote human health primarily by modifying the gut microbiota. This microbiota modification can further benefit the host's overall health *via* improvements in functional gut barriers, immunomodulation and beneficial effects on the gut–brain axis (Sánchez *et al*. 2017). During food fermentation, beneficial microorganisms with probiotic properties in these products produce several compounds/metabolites, such as antimicrobials, that enhance these therapeutic properties (Faraki *et al*. 2020).

The majority of the probiotics can be categorised under lactic acid bacteria (LAB) commonly isolated from fermented dairy products (fermented milk such as yoghurt and cheese), other fermented foods (kimchi and sauerkraut) and other sources such as meat, human breast milk and human faeces; however, some of these probiotic genera also naturally exist in the human lower intestine (Azad *et al*. 2018). The *Lactobacillus* and *Bifidobacterium* are two of the most predominant microorganisms in gastrointestinal microbiota and are currently the most understood probiotic genera, which are also highly commercialised for probiotic product formulation (Chen *et al*. 2017). Other promising probiotic species include genera *Lactococci*, *Streptococci*, *Bacillus*, *Escherichia*, *Propionibacterium* and yeast *Saccharomyces* (He and Shi 2017) and the next-generation probiotics from the genera *Bacteroides*, *Clostridium*, *Faecalibacterium* and *Akkermansia* (O'Toole *et al*. 2017). There are some safety concerns regarding certain probiotic genera, such as *Enterococcus* (considered pathogenic), which may potentially cause illness to the host (Ranadheera *et al*. 2017). Probiotics should resist gastric acid, enzymes, bile and other secretions during gastrointestinal transit and adhere to the intestinal epithelium sufficiently to deliver health benefits. Additionally, probiotics should be safe, nonpathogenic and noninvasive, capable of forming balanced microbiota in the host (Ranadheera *et al*. 2018).

Dairy foods both with bovine and nonbovine origin are the main probiotic and traditional vehicle in delivering probiotics to humans. However, compared to bovine milk, nonbovine milk is under-appreciated in this regard. Hence, this review focuses on nonbovine (goat, sheep, camel, buffalo and donkey) milk and milk products and their potential to act as a probiotic carrier. Major physicochemical, nutritional and sensory quality parameters of these products were also discussed.

BOVINE VS NONBOVINE MILK: A BRIEF COMPARISON

Bovine milk and its products remain the predominant dairy foods worldwide, accounting for around 81% of the total milk production in 2018 (FAO 2020). Nevertheless, since relatively recently, there is an increase in demand for nonbovine milk and its products (Nuñez and de Renobales 2016), such as goat (2.22%), sheep (1.26%), camel (0.37%), buffalo (15.1%) and donkey milk (FAO 2020). This trend is also followed in the probiotic market, where nonbovine milk as the alternative probiotic carrier showed an increase mainly ascribed to the different protein composition profile and protein amino acid sequences of these nonbovine milk, resulting in a potentially low cross-reactivity with cow milk proteins (Maryniak *et al*. 2022).

The compositions of some of the nonbovine milk compared to bovine milk are presented in Table 1. In addition to these differences in composition, there are other notable differences among these kinds of milk. Sheep milk has a relatively higher concentration of fat globules with smaller particle sizes than bovine milk (3.6 μm in sheep milk vs 4.0 μm in bovine milk) (Balthazar *et al*. 2017a, 2017b), as well as goat milk fat droplets (3.0 μm) (Gantner *et al*. 2015). This characteristic may contribute to the better freezing stability of sheep and goat milk products by reducing phase separation (Park and Pariza 2007). As food proteins can cause allergenic reactions in sensitive individuals, allergic reactions to bovine casein and whey proteins (Masoodi and Shafi 2010) can occur. However, there are some reports indicating less allergenic reactions to some nonbovine milk (particularly from small ruminants) due to the concentration and polymorphism in those milk (El-Agamy 2007). For example, due to the high amino acid sequence identity with cow milk proteins, goat and sheep milk proteins would be a better choice for cow milk allergy prevention than camel and donkey milk proteins. Generally, donkey proteins possess a lower sequence identity with cow milk allergens than proteins from camel milk (Maryniak *et al*. 2022). Further research is necessary for this area as some people present hypersensibility to goat and sheep milk (Gunaydin *et al*. 2021).

Buffalo milk also tends to have higher levels of fats, proteins, lactose (Table 1), vitamin A, vitamin C and calcium than bovine milk. However, buffalo milk has a lower vitamin E and cholesterol (El-Salam and El-Shibiny 2011). In addition, buffalo milk exhibits a higher buffering capacity (acidification capacity) than bovine milk (Ahmad *et al*. 2008).

Camel milk is relatively less popular in the western world; nevertheless, it is an important food source in semi-arid and arid regions, especially in Africa, Gulf Cooperation Council and Middle Eastern countries (Singh *et al*. 2017). The presence of multiple β-casein structures and the absence of β-lactoglobulin in camel milk may result in a hypoallergenic response once consumed, presenting hypersensibility to these specific proteins (Abrhaley and Leta 2018). Hence, some western countries are now actively seeking the development of agricultural enterprises to fully utilise the potentials associated with camel milk. Recent studies suggested that some bioactive components in camel milk, such as bioactive peptides and proteins, are potentially responsible for improved immune functions and antimicrobial properties towards pathogenic microorganisms (Abrhaley and Leta 2018). Fermented camel milk has potential health benefits, including ACE-I activity and antimicrobial effects (Alhaj *et al*. 2018). However, camel milk does not form a desirable curd during lactic acid fermentation. The fermented camel milk products have a watery consistency and a fragile and poor structure caused by the large size of casein micelles and the relative distribution of casein fractions (Abou-Soliman *et al*. 2017).

Donkey milk can also be considered a food source with potentially lower allergenic properties than bovine milk (Martini *et al*. 2018). The composition of donkey milk is reported as relatively similar to human breast milk in the

Table 1 Gross composition and physicochemical properties of different nonbovine milk and bovine milk.

Parameter	Goat	Sheep	Camel	Buffalo	Donkey	Bovine
Total dry matter (%)	12.4 ± 0.7	17.1 ± 1.4	12.81 ± 0.01	18.64 ± 0.72	11.04	12.73
Protein (%)	3.70 ± 0.01	5.50 ± 1.10	2.33 ± 0.07	4.70 ± 0.20	1.72	3.42
Fat (%)	3.80 ± 0.10	5.90 ± 0.30	4.10 ± 0.15	8.30 ± 0.30	0.38	4.09
Lactose (%)	4.10 ± 0.40	4.80 ± 0.40	4.81 ± 0.62	4.80 ± 0.20	6.88	4.82
Ash (%)	0.80 ± 0.10	0.90 ± 0.10	0.73 ± 0.03	0.84 ± 0.02	0.47	0.72
pH	6.38 ± 0.08	6.63 ± 0.04	6.13 ± 0.11	6.81 ± 0.06	7.1	6.30 ± 0.15
Titratable acidity (%)	0.18 ± 0.03	0.23 ± 0.01	0.17 ± 0.01	0.18 ± 0.03	-	0.16 ± 0.04
References	Mahmood and Usman (2010); Legesse *et al*. (2017)	Mahmood and Usman (2010)	Legesse *et al*. (2017); Yadav *et al*. (2015)	Mahmood and Usman (2010); Pesce *et al*. (2016)	Guo *et al*. (2007); Numpaque *et al*. (2019)	Legesse *et al*. (2017); Numpaque *et al*. (2019)

lactose, total proteins and whey proteins levels, being that the reason for lower hyperallergenicity. Donkey milk is rich in essential amino acids and polyunsaturated fatty acids (PUFAs) (α-linolenic acid and linoleic acid) (Guo *et al*. 2007; Barłowska *et al*. 2011). Moreover, the presence of a higher level of antibacterial components, including immunoglobulins, lactoferrins, lysozymes and lactoperoxidase, has been reported in donkey milk compared to bovine milk (Aspri *et al*. 2017).

PROBIOTICS IN NONBOVINE MILK PRODUCTS

Introducing probiotics in dairy products to improve functional benefits has been a popular practice in both commercial and research fields for decades. Although bovine milk is still dominating as the primary probiotic carrier matrix in commercial dairy development, there is an increasing interest in applying nonbovine milk as the probiotic carrier food due to their beneficial effects (Ranadheera *et al*. 2018). Historically, goat milk has been used to produce goat cheese, and it is also the most commonly used nonbovine milk as the probiotic carrier (Gomes and Malcata 1998). In recent years, other nonbovine milk, such as camel, donkey, buffalo and sheep milk, are also been extensively studied for their probiotic carrier potentials (Hamed and Elattar 2013).

Probiotics in nonbovine milk products: Microbiological properties/probiotic viability

The most critical aspect of probiotic product development is to maintain sufficient probiotic viability in the product. Significant losses of probiotic viability can be experienced during all stages of processing, transportation and storage. Therefore, ensuring enough live and active probiotic numbers at the time of consumption is critical to the probiotic food industry (Sangami and Sri 2017). Probiotic products are generally required to maintain the minimum satisfactory viability level of at least 10^6–10^9 cfu/mL or g of food product to ensure the claimed health benefits (Sagheddu *et al*. 2018). The viability levels of probiotics in different types of nonbovine milk products are widely varied depending on the storage temperature and duration (Ranadheera *et al*. 2018) (Table 2). However, in most cases, the viability levees are satisfactory and above the minimum therapeutic level.

Goat milk as a probiotic carrier

Goat milk possesses some desirable features for probiotics such as favourable pH, titratable acidity and acidification capacity, making them highly suitable for carrying probiotics during post-processing and gastrointestinal transit (Galina *et al*. 2007). Although goat milk is predominately used for cheese production (Gomes and Malcata 1998), probiotic yoghurt (Ranadheera *et al*. 2012b), probiotic-enriched fermented goat milk (Martín-Diana *et al*. 2003) and other products such as microencapsulated probiotic goat milk powders (Ranadheera *et al*. 2015) have been produced and are slowly finding their way on the consumer market in addition to being extensively researched.

Two main types of goat cheese (Coalho and Feta) have been studied for their capacity for probiotic fortification. Probiotic strains *Lactobacillus acidophilus* La-5, *Lacticaseibacillus casei* subsp. *paracasei* (*L. casei* 01) and *Bifidobacterium lactis* (BB12) were fortified in Coalho cheese, and the results indicated 10^7–10^8 cfu/g of probiotic viability during storage (de Oliveira *et al*. 2014). In another study, *L.*

Table 2 Recent studies covering nonbovine dairy products containing probiotic strains.

Type of Milk	Dairy food	Product	Probiotic Strain	Viability at the end of storage (log cfu/g)	Storage condition and period	Remarks	Reference
Goat	Cheese	Boursin-type goat cheese	*B. lactis* *L. rhamnosus*	~7 ~8	4 ± 2°C 35 days	*B. lactis* was suggested to have higher resistance to simulated gastric and enteric juices than *L. rhamnosus*, log 0.2 and log 4.0 cfu/g respectively	Martins *et al.* (2018)
		Brazilian semihard goat milk cheese (Coalho)	*L. acidophilus* *L. paracasei* *B. lactis*	~7 ~7 ~7	10°C 28 days	No significant differences ($P > 0.05$) were observed in the five cheese samples	Bezerra *et al.* (2017)
		Creamy goat cheese	*L. acidophilus* LA-5 *B. lactis* BB-12	~6 ~6	7°C 21 days	6% of inulin was applied to produce symbiotic cheese, and no negative effect was observed in cheese acceptance	Barbosa *et al.* (2016)
		Traditional semihard goat cheese	*L. acidophilus* *B. lactis*	~6 ~7	6°C 70 days	*B. lactis* can slightly grow in cheese but it depends on physiochemical parameters, whereas *L. acidophilus* did not grow in any experimental cheese	Gomes and Malcata (1998)
		Coalho goat cheese	*L. acidophilus* LA-5 *B. lactis* BB-12 *L. casei* 01	~7–8	Right after fermentation	Decreased to log 5.5–6.0 cfu/g after simulated digestion	de Oliveira *et al.* (2014)
		Probiotic goat cheese	*L. mucosae* CNPC007	~8	4°C 28 days	*L. mucosae* CNPC007 fortified with goat milk showed good resistance to freeze-drying process	de Moraes *et al.* (2018)
Goat	Cheese	Probiotic Feta cheese	*P. freudenreichii* subsp. *Shermanii* LMG 16424 T	~9	3°C 60 days	Probiotic viability increased until day 7 and maintained constant till the end of maturation	Angelopoulou *et al.* (2017)
		Probiotic Feta cheese	*L. paracasei* K5	~6	4°C 90 days	Potentially symbiotic immobilised biocatalyst (delignified wheat bran prebiotic carrier) enhanced aromatic characteristics of cheese and prevented possible spoilage or pathogenic microorganisms	Terpou *et al.* (2019)
	Yoghurt	Yoghurt with added Isabel grape (*Vitis labrusca L.*) preparation	*L. acidophilus* LA-5	~7–8	5 ± 0.5°C 28 days	Antagonism between *L. acidophilus* LA-5 and *L. bulgaricus* was observed	Silva *et al.* (2017)
		Goat yoghurt with honey	*L. acidophilus* LA-5	~6	4 ± 2°C 28 days	The presence of honey increased probiotic counts (~log 1 cfu/g) until 21 days	Machado *et al.* (2017)
		Fermented goat milk with grape pomace extract	*L. acidophilus* LA-5	~5	4°C 28 days		Dos Santos *et al.* (2017)

(continued)

Table 2 (Continued).

Type of Milk	Dairy food	Product	Probiotic Strain	Viability at the end of storage (log cfu/g)	Storage condition and period	Remarks	Reference
	Fermented Goat milk		*L. rhamnosus* HN001	~7		The phenolic content in grape pomace extract did not influence the viability of probiotic strains during 28 days of storage	
		Fermented goat milk beverage with grape juice and/or grape pomace	*L. rhamnosus*	~7	5 ± 1°C 28 days	No significant decrease was observed in simulated stomach digestion, about log 0.6 reduction was observed in simulated duodenum digestion	Freire *et al*. (2017)
		Fermented dairy drink	*L. acidophilus* LA-5 *B. lactis* BB-12 *P. jensenii* 702	~7–8 ~7–8 ~7–8	7°C 21 days	Potential synergistic effect was observed in LA-5 co-cultured with 702. 702 may have equipped mechanism that enables better survival under cold storage than LA-5 and BB-12	Ranadheera *et al*. (2016)
Goat	Ice cream	Functional ice cream with *M. communis* fruit pulps	*L. casei 431*	~7	−20°C 28 days	log 0.80–1.32 unit of probiotic counts was decreased potentially due to the mechanical damage during freezing storage, and the addition of fruit pulp did not significantly alter the probiotic potential	Öztürk *et al*. (2018)
		Chocolate-flavoured probiotic ice cream	*L. acidophilus* LA-5 *B. lactis* BB-12 *P. jensenii 702*	~7–8 ~7–8 ~7–8	−20°C 364 days	Packaging materials did not influence the probiotic viability during storage	Ranadheera *et al*. (2013)
	Frozen yoghurt	Goat frozen yoghurt with the addition of probiotic and prebiotic as adjunct	*L. acidophilus* *B. lactis*	~4 ~5	−18°C 120 days	Relatively acceptable probiotic viability was observed at day 7 (~log 5–7 cfu/g)	Alves *et al*. (2009)
	Other products	Microcapsul (in alginate dairy-based matrices)	*B. longum* subsp. *infantis*	~8	4°C 28 days	A significant decrease in probiotic viable counts was observed in free probiotic samples during storage and *in vitro* digestion	Prasanna and Charalampopoulos (2018)
		Freeze-dried powder and tablet	*L. acidophilus*	~6–8	4 and −18°C 180 days	Survival rate of freeze-dried *L. acidophilus* was up to 93.9% ± 0.12% and presented good stability at low temperature	Shu *et al*. (2018)
Sheep	Cheese	Probiotic Feta cheese	*P. shermanii*	~9	18°C 60 days	The viability of propionic acid bacteria gradually increased from log 6.8 to log 8.9 cfu/g during cheese maturation	Angelopoulou *et al*. (2017)
		Functional Scamorza cheese from ewe's milk	*L. acidophilus*	~7 ~9	8–10°C 15 days	Thermophilic lactobacilli and lactococci were 4.3 ± 0.03 and 4.1 ± 0.02 log10 cfu/g in LA and BB respectively. Mesophilic	Albenzio *et al*. (2013)

(continued)

Table 2 (Continued).

Type of Milk	Dairy food	Product	Probiotic Strain	Viability at the end of storage (log cfu/g)	Storage condition and period	Remarks	Reference
			Mix of the *B. longum and B. lactis*			lactobacilli and lactococci were 4.3 ± 0.03 and 3.1 ± 0.02 log10 cfu/g in LA and BB respectively	
Sheep	Cheese	Probiotic soft sheep's cheese	*L. acidophilus* LA-5 *B. lactis* BB-12	~8 ~8	4°C 30 days	The addition of probiotic bacteria in experimental cheeses did not affect starter viability	Cuffia *et al.* (2018)
	Yoghurt	Sheep milk yoghurt and yoghurt with mixture of cow and sheep milk (cow/sheep ratios of 3:1, 1:1 and 1:3)	*L. acidophilus* LA-5	>8	4°C 28 days	The highest probiotic viability was observed in 1:3 ratio of cow and ewe milk samples, which is log 9.5 cfu/g	Vianna *et al.* (2017)
		Sheep milk yoghurt from probiotic and symbiotic matrix with addition of grumixama fruit pulp	*B. lactis* BB-12	~7	Right after fermentation	The addition of grumixama pulp did not influence the viability of the starter culture or probiotic	Silva *et al.* (2019)
	Fermented sheep milk	Fermented probiotic sheep milk	*L. casei* 431	12	4°C 28 days	*L. casei* 431 presented good viability during refrigerated storage and did not impose any harm on dental enamel (*in vitro*), also microhardness loss decreased	Nadelman *et al.* (2017)
		Fermented probiotic sheep milk	*L. casei* 01	>9	4°C 28 days	*L. casei* 01 showed a tendency to control internal enamel demineralisation and good viability during refrigerated storage	Nadelman *et al.* (2019)
		Fermented synbiotic sheep milk strawberry juice	*L. plantarum* CECT_8328	>9	4°C 30 days	Probiotic remained stable/viable during refrigerated storage and after *in vitro* simulated digestion (>log 6.4 cfu/g), and also improved bioactive compounds especially when combined with fibres	Balthazar *et al.* (2019)
		Fermented probiotic sheep milk	*L. acidophilus* LA-5 *B. lactis* BB-12	~6 ~6	4°C 42 days	LA-5 and BB-12 showed better viability in fermented sheep milk than in other milk types	Varga *et al.* (2014)
	Ice cream	Probiotic full-fat sheep milk ice cream and symbiotic nonfat sheep milk ice cream with inulin	*L. casei* 01	>6	−18°C 150 days	Addition of inulin appeared as a primary protection for probiotics, but its function diminished with storage	Balthazar *et al.* (2018)
		Probiotic full-fat sheep milk ice cream	*L. casei* 431	12	−18°C 28 days	*L. casei* 431 presented in good viability during frozen storage and did not impose	Nadelman *et al.* (2017)

(continued)

Table 2 (Continued).

Type of Milk	Dairy food	Product	Probiotic Strain	Viability at the end of storage (log cfu/g)	Storage condition and period	Remarks	Reference
						any harm on dental enamel (*in vitro*), also microhardness loss decreased	
Camel	Cheese	Low-fat Akawi cheese	*L. plantarum*	~7	4°C 21 days	No significant difference in probiotic viability was obtained regardless of the culture used and exopolysaccharide-producing capacity	Al-Dhaheri *et al.* (2017)
	Fermented camel milk	Probiotic fermented camel milk	*L. reuteri* KX (8817)77 *L. plantarum* KX881772 *L. plantarum* KX881779	>9 >8 >8	4°C 21 days	Control strain *LP.DSM* showed higher population in fermented bovine milk, and other three camel milk strains showed no significant difference between the two milk types	Ayyash *et al.* (2018b)
Camel	Fermented camel milk	Probiotic fermented camel milk with inulin as adjunct	*L. acidophilus* *Mix culture of L. acidophilus and B. lactis*	~7 ~8	4 ± 1°C 14 days	6% of inulin showed best probiotic viability in both samples	Ibrahim and Khalifa (2013)
		Probiotic fermented camel milk	*L. acidophilus* *B. lactis*	~6 ~6	4°C 42 days	Camel milk can be considered a good probiotic carrier candidate	Varga *et al.* (2014)
	Frozen yoghurt	Probiotic camel milk frozen yoghurt	*B. infantis* DSM 20088 *B. angulatum* DSM 20098	~8 ~8	−20°C 42 days	Higher viscosity, lower fat destabilisation and lower melting rate were obtained in camel milk ice cream compared to cow milk ice cream	AL-Saleh *et al.* (2011)
Buffalo	Yoghurt	Probiotic buffalo yoghurt	*L. acidophilus* LA-5 *B. lactis* BB-12	~5 ~7	4°C 28 days	Bovine yoghurt exhibited better performance in terms of probiotic viability (both strains >log 7 cfu/g	Nguyen *et al.* (2014a, 2014b)
		Buffalo yoghurt incorporated with microencapsulated probiotics	*L. acidophilus*	>7	4°C 28 days	Microencapsulated culture cannot withstand the human stomach pH (pH 1–3)	Shoji *et al.* (2013)
	Cheese	Probiotic buffalo Ricotta cheese	*L. acidophilus* LA-5	>7	4°C 12 days	Probiotics were almost stable during 12 days of storage, from 7.87 to 7.6 cfu/g, exhibited in 3.43% of log reduction	Sameer *et al.* (2020)
		Probiotic buffalo Cheddar cheese	*L. acidophilus* LA-5 *B. bifidum* BB-11	>7 >7 >7	4–6°C and 12–14°C 180 days	High maturation temperature results in relatively lower probiotic survivability in all three strains, and three strains were all stable during storage	Murtaza *et al.* (2017)

(continued)

Table 2 (Continued).

Type of Milk	Dairy food	Product	Probiotic Strain	Viability at the end of storage (log cfu/g)	Storage condition and period	Remarks	Reference
			B. longum BB536				
Donkey	Fermented donkey milk	Donkey milk fermented by probiotics isolated from Parmigiano Reggiano cheese	*L. rhamnosus* AT 194	~8	4 ± 0.02°C 30 days	Three strains all exhibited ~log 2 increase in probiotic counts from day 1 to day 7 and gradually decreased to ~log 8.0 cfu/mL	Chiavari *et al*. (2005)
			L. rhamnosus CLT 2/2	~8			
			L. casei LC 88	~8			
Donkey	Fermented donkey milk	Donkey milk fermented with *Lactobacillus* sp.	*L. acidophilus*	>9	After 48 h fermentation	Probiotic viability during storage was absent in this research	Nazzaro *et al*. (2010)
			L. bulgaricus	>9			
			L. paraplantarum	>9			
			L. plantarum	>9			
			L. pentosus	>9			
		Donkey milk fermented with *Lactobacillus sp*.	*L. rhamnosus*	>9	After 48 h fermentation	Probiotic viability during storage was absent in this research	Nazzaro *et al*. (2010)
		Probiotic fermented donkey milk	*L. acidophilus*	~6	4°C 30 days	Significant reduction in probiotic viability was observed in both strains, generally from log 8 cfu/mL on day 1 to ~ log 6 cfu/mL on day 30	Perna *et al*. (2015)
			L. casei	~6			

mucosae CNPC007, a potential probiotic strain isolated from raw goat milk, was incorporated into Coalho cheese. *L. mucosae* CNPC007 showed higher viability (10^8 cfu/g) in goat cheese during a storage period of 28 days (de Moraes *et al*. 2018). *Propionibacterium freudenreichii* subsp. *shermanii* was previously studied by Jan *et al*. (2002), which indicated induced apoptosis of colorectal carcinoma cells in both *in vitro* and *in vivo* studies (Lan *et al*. 2008). *P. freudenreichii* subsp. *shermanii* LMG 16424 T was applied as the adjunct in producing Feta cheese. High viability of this probiotic strain was observed at the end of the maturation period (~10^9 cfu/g) (Angelopoulou *et al*. 2017). *L. paracasei* K5 was also applied as the potential probiotic adjunct to produce Feta-type cheese. *L. paracasei* K5 was incorporated with delignified wheat bran carrier and manufactured into cheese. Over 10^6 cfu/g of probiotic viability was observed after 90 days of maturation and storage period (Terpou *et al*. 2019).

Goat milk yoghurt production is challenging due to the difficulty in imitating the particular consistency and rheology characteristics of the currently available bovine milk yoghurt-style product. This difficulty is primarily due to the lack of αs1-casein in goat milk (Miocinovic *et al*. 2016), a significant curd constituent. *L. acidophilus* La-05 was inoculated with goat milk to produce goat milk yoghurt with honey to improve technological and sensory characteristics. Over 10^6 cfu/g of *L. acidophilus* La-05 was observed in all yoghurt formulations after 28 days of refrigerated storage, where the presence of honey may positively influence the probiotic viability during storage (Machado *et al*. 2017). In another study, two probiotic strains, *L. acidophilus* LA-5 or *Lacticaseibacillus rhamnosus* HN001, were incorporated to make fermented goat milk with the addition of grape pomace extract. *L. acidophilus* LA-5 appeared to maintain significantly lower viable counts, while *L. rhamnosus* HN001 showed acceptable viability levels of at least 10^7 cfu/mL during storage (Dos Santos *et al*. 2017). Other related probiotic dairy products, such as probiotic ice cream and probiotic-enriched frozen yoghurt made with goat milk, were reported in the literature (Ranadheera *et al*. 2013) (Alves *et al*. 2009). Generally, goat milk was identified as a suitable carrier matrix for maintaining probiotic viability during the processing and storage of probiotic goat milk products. However, the viability of probiotics in such products during processing and shelf life varies depending on the strains and additives used (Table 2).

Sheep milk as a probiotic carrier

Relatively high levels of fat (6.0%) and protein (5.5%) in sheep milk can promote probiotic viability, particularly in cheese and ice cream. These macronutrient characteristics provide a denser structure in solid or semisolid products such as cheese and ice cream, which forms a better protective matrix for probiotics against degradation during storage (Balthazar *et al*. 2017a). Sheep milk is a promising food matrix that delivers enough probiotic bacteria to guarantee their health benefits and improve biocompounds presented in dairy products (Balthazar *et al*. 2019, 2018).

Several studies have been orientated towards the probiotic enrichment in sheep milk cheese. For example, *L. acidophilus* LA-5 and mixed culture of *B. longum* BL-46 and *B. lactis* BB-12 were incorporated in Scamorza ewe milk cheese. *L. acidophilus* LA-5 viability was reported to be log 7.55 ± 0.07 cfu/g, and the total *Bifidobacterium* viability was log 9.09 ± 0.04 cfu/g in mixed culture samples (Albenzio *et al*. 2013). Similarly, when *L. acidophilus* LA-5 and *B. lactis* BB-12 were individually formulated with a cheese starter culture to make soft sheep cheese, viability levels of *L. acidophilus* and *B. lactis* BB-12 LA-5 at the end of 30 days of maturation were log 8.15 ± 0.13 and log 7.99 ± 0.17 cfu/g respectively (Cuffia *et al*. 2018).

Sheep milk also contains a higher buffering capacity than bovine milk, which provides faster acidification and favours the growth of certain probiotics, such as *B. longum*, at the early stage of the fermentation process (Kehagias *et al*. 2008). The survival rate of *L. acidophilus* LA-5 and *B. lactis* BB-12 in fermented sheep milk during 6 weeks of storage was observed by Varga *et al*. and reported satisfactory viability of log 6.53 ± 0.40 and log 6.80 ± 0.16 cfu/mL respectively (Varga *et al*. 2014). In another study, *B. lactis* BB-12 was also evaluated in probiotic-only and symbiotic (fructo-oligosaccharide) sheep yoghurt with the addition of grumixama fruit pulp during fermentation and resulted in ~log 7 cfu/mL in both samples (Silva *et al*. 2019).

Camel milk as a probiotic carrier

Several lactic acid bacteria strains, including *L. plantarum*, *L. pentosus and L. lactis lactis*. *Streptococcus* and *Enterococcus*, were isolated from raw camel milk and showed antagonist characteristics against pathogenic bacteria (Yateem *et al*. 2008; Abushelaibi *et al*. 2017; Ayyash *et al*. 2018a). Probiotic strains *L. reuteri*-KX881777, *L. plantarum*-KX881772 and *L. plantarum*-KX881779 were used in producing fermented camel milk and stored for 21 days under refrigerated conditions. Both *L. plantarum* strains could maintain above 10^8 cfu/mL of probiotic viability during 21 days of storage, while *L. reuteri* showed a better survival rate with more than 10^9 cfu/mL (Ayyash *et al*. 2018b). Another study by AL-Saleh *et al*. evaluated the probiotic viability of *B. infantis* DSM 20088 and *B. angulatum* DSM 20098 in frozen yoghurt made from either camel or bovine milk. Results indicated no significant ($P > 0.05$) reduction in probiotic viability during 6 weeks of storage from their initial viability counts of ~10^8 cfu/g (AL-Saleh *et al*. 2011). In another study, *L. acidophilus* (LA) and *B. bifidum* (BB) were used to produce probiotic fermented camel milk and prebiotic inulin was applied to enhance the overall product quality. All samples had acceptable probiotic viability above 10^7 cfu/mL during storage. However, 6% inulin addition showed the best probiotic viability for 14 days of storage in both LA and LA and BB mix culture samples. Furthermore, there was only a relatively small ($P > 0.05$) reduction in viability levels from log 8.27 to 7.65 cfu/mL in LA and from log 8.87 to 8.28 cfu/mL in LA and BB mix culture (Ibrahim and Khalifa 2013). Similarly, another research indicated a slight decrease in *L. acidophilus* (from log 6.71 to 6.36 cfu/mL) and *B. lactis* (from log 6.39 to 6.24 cfu/mL) in fermented camel milk at the end of 42 days of cold storage (Varga *et al*. 2014).

Buffalo milk as a probiotic carrier

A higher proteolytic activity and a better growth rate of yoghurt starter cultures (*S. thermophilus* and *L. delbrueckii* subsp. *bulgaricus*) were reported in fermented buffalo milk (unhomogenised and unstandardised) compared to bovine milk (Khanna and Singh 1979). Due to the higher concentration of protein and fat content in buffalo milk, buffalo yoghurts possess higher protein and fat contents than yoghurt made from bovine, goat and sheep milk (Mymensingh 2007). A comparative study of probiotic yoghurt made from buffalo and bovine milk demonstrated that *L. acidophilus* LA-5 viability was decreased from log 7.26 ± 0.12 to log 5.17 ± 0.08 cfu/g while *B. lactis* BB-12 showed better viability (7.04 ± 0.17 log cfu/g) in the same buffalo yoghurt for 21 days of refrigerated storage. Yoghurt made from bovine milk showed better performance, and both probiotic strains appeared in acceptable viability (above log 7 cfu/g) at the end of storage (Nguyen *et al*. 2014a, 2014b). Similarly, another study focused on applying microencapsulated probiotics (via complex coacervation followed by lyophilisation drying) in buffalo yoghurt. The viability of microencapsulated *L. acidophilus* LA-5 (>log 7 cfu/g) was almost log 4 cfu/g higher than their free counterparts at the end of 28 days of storage. However, microencapsulated probiotics did not survive well in the presence of human stomach pH levels (pH 1–3) (Shoji *et al*. 2013). The viability of *L. acidophilus* LA-5 in buffalo Ricotta cheese was reported to be above log 7.5 cfu/g throughout the 12 days of storage under refrigeration. Only a 3.43% of log reduction was observed between the initial (log 7.87 cfu/g) and final count (log 7.6 cfu/g) (Sameer *et al*. 2020). Murtaza *et al*. evaluated the probiotic survivability during buffalo milk Cheddar cheese maturation up to 180 days. All three probiotic strains (*L. acidophilus* LA-5, *B. bifidum* BB-11 and *B. longum* BB536) remained above log 7 cfu/g in both standards (4–6°C) and elevated (12–14°C) maturation temperatures (Murtaza *et al*. 2017). Despite many challenges, buffalo milk and its products can be considered good probiotic carriers (Abesinghe *et al*. 2020; Priyashantha *et al*. 2021).

Donkey milk as a probiotic carrier

Due to the low protein and fat content, donkey milk can only form weak coagulum at acidic conditions, making it challenging to produce cheese-type products. However, donkey milk has been used in producing fermented beverages (Chiavari *et al*. 2005; Aspri *et al*. 2017). In a previous study, probiotic strains *L. rhamnosus* (AT 194, GTI/1, GT 1/3 and RBM 514) were inoculated in pasteurised donkey milk to produce fermented drinks. All strains maintained satisfactory viability levels even at low pH (3.7–3.8) at the end of 15 days of cold storage. This could be due to high lactose content of donkey milk. (Coppola *et al*. 2002). This indicates the importance of the nondairy milk composition on their ability in delivering probiotics to humans. In another study, three probiotic strains isolated from Parmigiano Reggiano cheese *L. rhamnosus* AT 194, CLT 2/2 and *L. casei* LC 88 were incorporated in producing fermented donkey milk. All strains exhibited high viability (~log 8 cfu/mL) after 30 days of storage. Donkey milk also contains high lysozyme content. Lysozyme possesses antimicrobial properties (Coppola *et al*. 2002; Chiavari *et al*. 2005) and this could affect the viability of probiotics in these products.

In another study, the viability of different strains of *Lactobacillus* sp. (*L. acidophilus*, *L. delbrueckii* subsp. *bulgaricus*, *L. paraplantarum*, *L. plantarum*, *L. pentosus and L. rhamnosus*) in fermented donkey milk was investigated. All strains could grow in donkey milk during 48 h of fermentation with a viable count above log 9 cfu/mL at the end. However, this study did not report the probiotic viability during storage (Nazzaro *et al*. 2010). Nevertheless, a relatively recent study by Perna *et al*. suggested that the viability of probiotic strains *L. acidophilus* and *L. casei* decreased significantly ($P < 0.05$) in fermented donkey milk beverage after 30 days of storage (from log 8.80 cfu/mL to log 6.75 cfu/mL and from log 8.28 cfu/mL to log 6.56 cfu/mL, respectively) (Perna *et al*. 2015).

Functional and technological properties of probiotics in nonbovine milk products

Functional and technological properties of probiotics including gastrointestinal tolerance, intestinal epithelium adhesion, immunomodulation and antagonistic and antimutagenic properties are essential for maintaining their therapeutic properties. Despite the probiotic viability during processing and storage, probiotic carrier matrices can also significantly influence these functional and technological properties (Ranadheera *et al*. 2010). Food matrix can provide protective functions to probiotics against harsh gastrointestinal conditions as well as physical damage during processing and delivery. For example, high protein and fat content in cheese can provide a barrier function for probiotic against gastric and intestinal juices during gastrointestinal digestion (Valerio *et al*. 2006). Additionally, prebiotics can modulate the functional characteristics of probiotics when symbiotically incorporated with probiotics in the food matrix (Buriti *et al*. 2010). The differences in compositional, physicochemical and nutritional attributes of nonbovine milk can impact the technological and functional properties of probiotics in these products.

Gastrointestinal tolerance

Food after ingestion is transferred to the stomach for primary digestion. The low pH (commonly pH 2.5–3.5 and can reach pH 1–2 depending on the secretion of gastric fluid) and antibacterial characteristics of pepsin can significantly threaten the survival of probiotics in these food products (Delgado *et al*. 2015). After 2–4 h of gastric digestion, food passes to the small intestine for further digestion. The probiotics are exposed to pH 7.0–8.0 with bile salt and pancreatic enzymes in the small intestine (Venema *et al*. 2019).

Probiotics *L. acidophilus* LA-5, *B. lactis* BB-12 and *P. jensenii* 702 were included in ice cream, plain and fruit yoghurt manufacturing to observe the probiotic performance during product storage and simulated gastrointestinal conditions (Ranadheera *et al*. 2012a). All samples showed significant ($P < 0.05$) declines in probiotic viability at pH 2 during gastric digestion. However, all probiotic strains in ice cream showed better survivability at pH 2 (from log 7 to log 3–5 cfu/g at 180 min of gastric digestion) than yoghurt. All three probiotic strains showed better viability levels at pH 3 and 4 during gastric digestion (approximately up to log 7 cfu/g). All samples experienced a log 3–4 reduction of probiotic viability with bile salt during 240 min intestinal digestion except the *B. lactis* BB-12 in goat ice cream (~log 7 cfu/g). In another study, *in vitro* gastrointestinal survival was examined in goat Coalho cheese incorporated with *L. acidophilus* LA-5, *L. casei* 01 and *B. lactis* BB-12. Initial viable counts of log 7–8 cfu/g in all samples reduced to logs 6.0, 5.7 and 5.5 cfu/g, respectively, after 180 min of *in vitro* gastrointestinal digestion. When probiotic *L. casei* 01 and *B. lactis* BB-12 in MRS broth were subjected to the same gastrointestinal conditions, no viable counts were observed after 122 min of digestion. Hence, goat Coalho cheese can be considered a protective food matrix for these probiotics (de Oliveira *et al*. 2014). A study by Hassanzadazar *et al*. examined the gastrointestinal tolerance of *L. plantarum*, *L. casei* and *L. delbru*eki, isolated from Koozeh cheese, traditionally made from sheep milk. The viable counts in all strains decreased significantly ($P < 0.05$) when exposed to pH 3, and no viable count was observed when pH was ≤2.0. *L. plantarum* and *L. casei* appeared in relatively higher bile salt resistance, but no strains can survive at 0.3% bile concentration (Hassanzadazar *et al*. 2012). In this study, all probiotic strains were grown in MRS agar and directly proceeded to the gastrointestinal test; hence, this low survivability could be due to the lack of a protective food matrix during gastrointestinal survival. In a study by Shori *et al*., *in vitro* gastrointestinal tolerance of *B. bifidum* was examined in probiotic cow and camel yoghurt enriched with *Cinnamomum verum* and *Allium sativum* water extract. High viable counts of *B. bifidum* (6.6×10^{10} cfu/mL) were observed in plain camel yoghurt and *C. verum* camel yoghurts after 1 h of gastric digestion where 9.7×10^9 cfu/mL was observed in *A. sativum* camel yoghurt. However, after 2 h of intestinal digestion, the probiotic viability decreased significantly to 4.85×10^9, 0.50×10^9 and 5.55×10^9 cfu/mL in plain, *A. sativum* and *C. verum* camel yoghurt respectively (Shori and Baba 2015). The findings of this study clearly demonstrate the effect of food matrix composition on the gastrointestinal survival of probiotics. A study by Verruck *et al*. compared the survival of *B. lactis* BB-12 in buffalo Minas Frescal cheese and MRS broth during *in vitro* gastrointestinal digestion. The initial viable probiotic counts before simulated digestion were log 8–9 cfu/g in both matrices. The survival rate of BB-12 decreased to 86.78% ± 6.27% and 91.10% ± 2.04% in MRS broth and cheese, respectively, after the simulated oesophagus–stomach digestion phase. The survival rate remains relatively low in MRS broth (93.42% ± 0.60%) but increased in cheese (109.55% ± 2.39%) during simulated duodenum digestion. This increase after duodenum digestion in probiotic cheese is mainly due to the recovery of sub-lethally injured cells but not due to cell division. These findings also indicated that buffalo cheese is a better food carrier matrix for probiotic delivery, probably due to the high-fat content in cheese, which consequently reduced the exposure of probiotics to bile salt (Verruck *et al*. 2015). Balthazar *et al*. (2019) performed *in vitro* gastrointestinal digestion assay on fermented sheep milk strawberry juice during 30 days of storage. They verified a significant drop (between log 2 and 3 cfu/mL) in *Lactiplantibacillus plantarum* CECT_8328 viability. However, the probiotic bacteria maintained the minimum required amount for the probiotic claim of more than log 6 cfu/mL.

Intestinal epithelial cell adhesion

A relatively limited number of studies investigated the intestinal epithelial cell adhesion of probiotics in nonbovine milk products. It is well recognised that probiotic microorganisms should be able to survive at a sufficient number during the gastrointestinal transit and colonise the intestinal epithelium. Adherence to intestinal epithelial mucosa is considered the prerequisite of probiotic intestinal colonisation (Alander *et al*. 1999). This colonisation can subsequently confer various health benefits, including the modulation of indigenous microbiota, enhancement of intestinal epithelial barrier, immuno-stimulation and extrusion of enteropathogens via competitive effects (Lim and Ahn 2012). The adhesion property is also considered strain and site specific (Moussavi and Adams 2010). Hence, intake of probiotic products with co-cultures may be beneficial leading to a high efficacy during cell adherence to the intestinal epithelium. However, this also can result in adverse effects due to the competition of adhesion sites by different strains (Ranadheera *et al*. 2014). A study by Ranadheera *et al*. reported the probiotic cell adhesion characteristics *in vitro* in ice cream, plain yoghurt and fruit yoghurt made by goat milk and subjected to co-cultures of *L. acidophilus* LA-5, *B. lactis* BB-12 and *P. jensenii* 702 (Ranadheera *et al*. 2012a). A significant difference in adhesion rate was observed in three probiotic strains from different carrier food matrixes, although a relatively low adhesion rate was presented in all samples. However, adhesion numbers were still able to reach 10^5–10^6 cfu/g. This study also indicated that the cell adhesion property of probiotics is strain and carrier food matrix dependent. The probiotic adhesion rate of *B. lactis* BB-12 appeared only 0.04% in plain goat yoghurt, while fruit goat yoghurt demonstrated 1.00%. Generally, fruity goat yoghurt resulted in a higher adhesion rate for these three probiotic strains, possibly due to certain substances in fruit juices that support the cell adhesion to Caco-2 cell lines. The lower adhesion rate in plain yoghurt can perhaps be explained by the competition of yoghurt starter culture against the probiotic strains when adhering to Caco-2 cell lines in plain yoghurt without fruit juices (Darilmaz *et al*. 2011) (Chaffanel *et al*. 2018).

A further study on probiotic adhesion of *L. acidophilus* LA-5, *B. lactis* BB-12 and *P. jensenii* 702 in fermented goat milk under mono- and co-culturing conditions was also reported in the literature (Ranadheera *et al*. 2014). The adhesion rate varied significantly from 0.03% for *P. jensenii* 702 co-cultured with *L. acidophilus* LA-5 to 2.78% for *P. jensenii* 702 co-cultured with *B. lactis* BB-12. Further, *B. lactis* BB-12 monoculture showed higher cell adherence than its co-cultured samples, mainly due to the absence of competition on the adhesion site when no other probiotic strains are involved. *B. lactis* BB-12 can also promote the adhesion of *P. jensenii* 702 when co-cultured, whereas *L. acidophilus* LA-5 tended to reduce the adhesion of *P. jensenii* 702 under co-culturing. When three strains were combined, this promoting ability of BB-12 declined. This finding is possible because that LA-5 is considered the primary coloniser, which has higher potency when combined with Caco-2 cell lines. Also, a study by Balthazar *et al*. evaluated the probiotic cell adhesion performance of *L. casei* 01 by adding inulin to sheep milk ice cream (Balthazar *et al*. 2018). More than log 5 cfu/g of probiotic adhesion was observed, corresponding to the findings followed by Ranadheera *et al*. (Ranadheera *et al*. 2012a). However, the adhesion rate was significantly high in this research (around 60%–70%) compared to Ranadheera *et al*. (Ranadheera *et al*. 2012a), possibly due to the different calculation methods used. The authors suggested that inulin showed no significant impact on probiotic adhesion in sheep milk ice cream. Still, the prolonged storage negatively influenced the cell adhesion ability of *L. casei* 01 (73%–79% adhesion on day 1 and 67%–75% adhesion on day 150) (Balthazar *et al*. 2018).

Immunomodulation and other functions

Only a few studies reported that the probiotic-enriched non-bovine milk products could alter other functional properties such as immune stimulation/modulation and angiotensin I-converting enzyme (ACE) inhibitory activity. Goat milk was fermented with probiotic strain *L. rhamnosus* CRL1505 which was initially isolated from goat milk. This probiotic strain maintained an acceptable viability (10^6 cfu/mL) in fermented goat milk. The probiotic fermented goat milk was supplemented with the immunocompromised malnourished mice. The results suggested that probiotic fermented goat milk can effectively accelerate the recovery speed in multiple clinical parameters during the repletion period from malnutrition in mice. Further, better resistance against intestinal and respiratory infections was also observed (Salva *et al*. 2011).

Inhibition of ACE can prevent the conversion of angiotensin I to angiotensin II, further lowering blood pressure (Vermeirssen *et al*. 2004). To evaluate their ACE inhibitory activity, goat milk was fermented with 28 *Lactobacillus* strains. Four probiotic strains: *L. reuteri* (95.92%), *L. delbrueckii* subsp. *bulgaricus* (84.61%), *L. rhamnosus* (82.79%) and *L. helveticus* (78.57%) showed high ACE inhibitory activity (Chen *et al*. 2012). Similar results have been observed when using fermented camel milk. *L. delbrueckii* subsp. *bulgaricus* NCDC (09) and *L. fermentum* TDS030603 (LBF) were used as the probiotic culture in this experiment, where this strain appeared in higher ACE inhibitory activity than LBF after 48 h of incubation at 37°C (76.75% ± 1.14% and 73.93% ± 0.74%, respectively) (Solanki *et al*. 2017). A study by Moslehishad *et al*. compared the ACE inhibitory performance and antioxidant activities among *L. rhamnosus* PTCC 1637-enriched fermented camel and bovine milk. In this study, *in vitro* ACE inhibitory activity, in general, had a higher IC50 value in fermented camel milk in comparison to bovine milk which may be potentially due to the higher proline content in camel milk (Moslehishad *et al*. 2013).

Hamed *et al*. suggested that camel milk fermented with the probiotic strain *Lactococcus lactis* subsp. *cremoris* can reduce kidney damage in CCl4-intoxicated mice (Hamed *et al*. 2018a, 2018b). The CCl4-intoxicated female mice were pre-treated with fermented camel milk daily for

15 days. As a result, a significant decrease in oxidative stress was observed, subsequently reducing renal dysfunction in mice. Ingestion of fermented camel milk in injured renal mice also presented in positive correlation with the reduction of creatinine, urea, uric acid, lactate dehydrogenase (LDH) and electrolytes levels in plasma (Hamed *et al*. 2018a, 2018b).

Physicochemical, nutritional and quality characteristics of probiotic-enriched nonbovine milk products

The physicochemical quality characteristics in probiotic-enriched nonbovine milk products can vary significantly due to various factors such as the composition of each type of milk and differences in added ingredients, processing and manufacturing techniques, product types, storage condition and time. However, the composition and physiochemical properties of different nonbovine milk and the probiotic strains used in processing can be the primary contributors to the physicochemical quality characteristics of final products.

pH and titratable acidity (TA)

Probiotic strains, storage period and product type influence the pH and TA of probiotic-enriched nonbovine milk products. The acidity of probiotic-enriched nonbovine milk products usually increases during storage. In the production of creamy goat cheese, the incorporation of probiotic strains *L. acidophilus* LA-5, *B. lactis* BB-12 and their co-cultures with 8% of inulin resulted in higher acid production during storage. The TA levels in probiotic-enriched cheese were increased from 1.1% to 1.7% ($P < 0.05$) after 21 days of storage, where a negligible amount of acids was produced in controlled cheese with only starter cultures. pH values also represented the same trends in this study (Barbosa *et al*. 2016). A lower pH was also observed in *L. paracasei* K5-fortified Feta cheese after 90 days of storage compared to control samples (Probiotic: pH 4.5 TA 1%–1.2%, control: pH 5.0 TA 0.8%) (Terpou *et al*. 2019). However, incorporating *B. lactis* and *L. rhamnosus* did not change the pH and TA in Boursin-type goat cheese, where pH and TA were ~4.4% and 0.5% lactic acid respectively (Martins *et al*. 2018). In another study, the addition of Isabel grape preparation into *L. acidophilus* LA-05-enriched goat milk yoghurt resulted in lower pH. This finding was due to the ability of grapes to provide more sugar for bacterial consumption, which resulted in more acid accumulation during storage (Silva *et al*. 2017). A study by Ranadheera *et al.* reported that the pH and TA in probiotic fermented goat milk were strain dependent. *L. acidophilus* LA-5 tends to produce more acids, resulting in lower pH (pH 4.74) and higher TA (0.64%) compared to *B. animalis* subsp. *lactis* BB-12 and *P. jensenii* 702. This finding was also reflected in the co-culture preparations. Co-cultures of LA-5, BB-12 and 702 together presented in lower pH and higher TA than their monocultures as well (Ranadheera *et al*. 2016). In contrast, no significant difference in pH and TA was observed in *P. freudenreichii* subsp. *shermanii* LMG 16424 incorporated sheep milk Feta cheese and control cheese during 90 days of storage (Angelopoulou *et al*. 2017). However, the Scamorza ewe milk cheese containing *L. acidophilus* and co-cultures of *B. longum* and *B. lactis* showed lower pH during the storage period than the control sample (Albenzio *et al*. 2013). The pH value of fermented camel milk with monocultures of probiotic strains *L. reuteri* KX881777, *L. plantarum* KX881772 and *L. plantarum* KX881779 (pH 4.3, 4.8 and 4.6, respectively) appeared to be much lower compared to their bovine counterparts (pH 5.1, 5.2 and 5.1, respectively) after 21 days storage (Ayyash *et al*. 2018b). The buffalo yoghurt fermented with *L. acidophilus* LA-5-free probiotic cultures exhibited significantly higher acidification for 28 days of storage than yoghurt with microencapsulated *L. acidophilus* LA-5 cultures. pH dropped to 4.01 after 28 days in free cultures with ~1.4% of acidity, where the pH and acidity of the microencapsulated sample were 4.2 and 1.0% respectively (Shoji *et al*. 2013).

Water-holding capacity, syneresis and viscosity

The water-holding capacity (WHC), syneresis and viscosity are significant quality parameters of nonbovine milk products enriched with probiotics. These quality parameters in yoghurt and fermented milk products are mainly related to the metabolism of probiotics and other associated lactic acid bacteria, which also can be caused by the yoghurt formation process (Costa *et al*. 2015). *Lactobacillus* sp. is generally considered the major contributor of viscosity in yoghurt and fermented milk *via* increasing the firmness of the preformed gel structure, while the increased syneresis (whey separation) can significantly reduce the viscosity during storage (Al Mijan *et al*. 2014; Costa *et al*. 2015). Probiotic *L. acidophilus* LA-5 was incorporated to produce goat milk yoghurt with the addition of Isabel grape preparation (IGP) and stored for 28 days at refrigerated conditions. This study obtained a relatively low syneresis level in 20 g/100 mL IGP addition (17.94%). WHC was decreased with the increased addition of IGP. This finding may be due to the low pH in IGP-incorporated yoghurt resulting in accelerated protein denaturation and reduced WHC. At the end of the storage period, yoghurt with 20% IGP showed the highest viscosity (158.1 mPa s), and yoghurt with 25% IGP directed lowest viscosity (53.8 mPa s), which can generally correspond with the syneresis and WHC in these samples (Silva *et al*. 2017). A study by Zamberlin *et al*. suggested that nonstandard heat-treated (60°C/5 min) sheep milk fermented with *L. rhamnosus* GG can significantly increase the syneresis to 33.83% ± 0.24% than standard heat treatment (95°C/5 min) with 29.70% ± 0.71% of syneresis. The yoghurt gel matrix can experience a higher predisposition when the temperature of heat treatment is lower than 85°C, leading to higher syneresis (Zamberlin and Samaržija 2017). The probiotic camel milk frozen yoghurt made with *B. infantis* DSM 20088 and *B. angulatum* DSM 20098 showed significantly higher viscosity (530.9 ± 1.2 mPa s) than cow milk frozen yoghurt, which is potentially due to the differences between fatty acid composition among two types of milk. Camel milk contains higher polyunsaturated fatty acids and long-chain saturated fatty acids with smaller fat globules compared to cow milk, leading to higher solidified fat and greater viscosity in its final products (AL-Saleh *et al*. 2011). In probiotic-enriched buffalo yoghurt, the syneresis was influenced by storage time and fermentation temperature. All samples showed increased syneresis with prolonged storage. At the same time, a higher fermentation temperature (43°C) resulted in a significantly higher syneresis rate (from 17.5% on day 1 to 19% on day 28) than a lower fermentation temperature (40°C and 37°C) with 14%–15% of syneresis. This result may be due to the rapid acidification under high temperatures during fermentation, leading to a weakened protein network (Nguyen *et al*. 2014a, 2014b).

Instrumental colour and textural analysis

In probiotic-enriched goat cheese products, most of the studies indicated a high brightness (L^*) value with the predominant yellowness (b^*) value compared to greenness (a^*) value during storage, which suggests a bright yellowish colour for goat cheese. Higher L^* value in goat milk cheese than in bovine cheese can be caused by its ability to convert β-carotene into vitamin A (Barbosa *et al*. 2016; Martins *et al*. 2018). Higher a^* values were reported in *B. lactis*- and *L. acidophilus*-enriched creamy goat cheese after 21 days of storage, which the production of green pigment can explain by complex B vitamins synthesised by probiotics during prolonged storage (Barbosa *et al*. 2016). A study by Silva *et al*. evaluated the instrumental colour of goat milk yoghurt enriched with IGP and *L. acidophilus*. A negative correlation was obtained between the increased addition of IGP and L^* and b^* values. The a* value increased with the addition of IGP due to anthocyanins in IGP (Silva *et al*. 2017). In *L. casei* 431, incorporating goat milk ice cream with white and blue myrtle fruit pulp as an adjunct and adding fruit pulp decreased the brightness (L^* 77.08 and 52.35 compared to Control L^* 84.08). Adding blue fruit pulp increased the redness (a^*: 7.86) and decreased yellowness (b^*: −1.50). The addition of white fruit pulp slightly enhanced the redness (a^*: 0.54) than control (a^*: −2.40) (Öztürk *et al*. 2018). The colour profile was evaluated in probiotic *L. acidophilus* La-5-enriched buffalo Ricotta cheese. However, instrumental colour values were statistically nonsignificant ($P > 0.05$) compared to controlled Ricotta cheese (Sameer *et al*. 2020).

The instrumental texture was analysed in *L. mucosae* CNPC007-enriched goat cheese. Hardness remained constant during storage, while a significant decrease in adhesiveness and springiness was observed with increased storage time. The acidification could cause this result during cheese maturation which further leads to proteolytic changes (de Moraes *et al*. 2018). Another study by Sameer *et al*. which evaluated buffalo Ricotta cheese with or without probiotic *L. acidophilus* La-5 demonstrated nonsignificant changes for instrumental texture analysis (Sameer *et al*. 2020). In a study by Balthazar *et al*., the textural differences were compared between different types of sheep milk ice cream: conventional full-fat, probiotic *L. casei*-enriched skim milk and symbiotic (*L. casei* and inulin) skim milk ice cream. Apparent viscosity was significantly varied among these products. The conventional ice cream showed the lowest viscosity with 61.87 ± 2.22 mPa s, while the highest viscosity was observed in symbiotic ice cream with 1632.03 ± 24.42 mPa s. The viscosity of probiotic ice cream was 276.07 ± 5.06 mPa s. Adding inulin can provide greater structural support for the product, resulting in higher viscosity. This result was reflected in hardness as well. No significant differences ($P > 0.05$) were observed in conventional and probiotic ice cream (46.79 and 42.58 N, respectively), while the hardness was almost doubled in symbiotic ice cream (88.01 N) (Balthazar *et al*. 2018).

Nutrient compositions

The nutritional compositions of probiotic-enriched nonbovine milk products, including protein, fat, carbohydrate, total solids and ash contents, are mainly determined by their primary ingredient profile, including milk types and any added ingredient (Zhang *et al*. 2015; Vianna *et al*. 2017). Usually, probiotic strains cannot significantly influence the nutritional composition of these products (Cuffia *et al*. 2018). A study by Vianna *et al*. suggested an increased total solid, fat, protein and ash content in probiotic-enriched cow-ewe milk yoghurt when the portion of ewe milk increased, which was due to the high protein and fat content in ewe's milk compared to cow milk (Vianna *et al*. 2017). In probiotic-fortified buffalo Cheddar cheese, the protein and fat content remained constant regardless of the probiotic strains used and maturation temperature for 180 days of storage. However, the moisture content decreased from 41% to 38% after 180 days of storage, but it was not influenced by probiotic strains and maturation temperature (Murtaza *et al*. 2017). The probiotic fermented goat milk beverages with grape juice and grape pomace extract showed a little protein and fat content difference. In contrast, higher carbohydrate and fibre content was observed in the grape pomace extract added formulation, mainly due to the added ingredient composition (Freire *et al*. 2017).

A study by Barbosa *et al*. compared the compositional differences in creamy goat cheese that each fortified with a traditional starter culture, *L. acidophilus* with 8% of inulin, *B. lactis* with 8% of inulin and mixed probiotic culture with 8% of inulin. A traditional starter culture observed higher protein and initial fat content, mainly due to adding prebiotics in other formulations. The mixed probiotic culture with 8% inulin presented the lowest protein content (6.4%), possibly due to the accelerated proteolytic activity by the synergistic effect of mixed probiotic culture. Fat content was significantly decreased in all samples from day 7 to day 21 due to intense lipolysis during maturation (Barbosa *et al*. 2016).

Sensory quality characteristics of probiotic-enriched nonbovine milk products

The sensory characteristics of probiotic products are considered one of the crucial factors during product development as it is directly related to consumer acceptability. Although many probiotic-enriched nonbovine milk products can retain their functionalities during storage and consumption, these products are usually shown to be rather unappealing during consumer sensory evaluations (Ranadheera *et al*. 2018). A typical example is the 'goaty' flavour in goat milk products, mainly due to short-chain fatty acids, such as caproic and caprylic acids, that are generally unappreciated by many consumers (Ranadheera *et al*. 2016). Nevertheless, specific probiotic strains are shown to produce organic substances during their metabolic processes, contributing to the development of unique flavours and aromas in final products. Furthermore, probiotic-enriched nonbovine milk products usually receive better sensory acceptance due to their unique flavour profile and traditional culinary uses. Goat cheese can be regarded as an ideal example of such a product that is highly acceptable by consumers (Dimitrellou *et al*. 2014). The sensory characteristics of probiotic nonbovine milk products are summarised in Table 3.

A lower sensorial acceptance was obtained in goat milk Coalho cheese with traditional starter culture rather than probiotic-enriched cheese samples. Cheese with *L. paracasei* and cheese with mixed culture *L. acidophilus*, *L. paracasei* and *B. lactis* were presented with the highest general perception score and purchase intention. *L. lactis* in traditional starter culture can exhibit high fermentability, rapidly converting carbohydrate sources into lactic acid and other organic compounds such as formate, acetate and ethanol, which can negatively influence the sensory profile. On the contrary, some other probiotic strains can produce organic compounds which give the cheese pleasant flavours under secondary proteolysis (Oliveira *et al*. 2012). In goat milk ice cream with *L. casei* and myrtle fruit pulp (blue and white), probiotic fortification without fruit addition showed the lowest sensory score due to the pH drops that negatively impacted the taste and flavour. Adding fruit into probiotic ice cream presented higher acceptability since adding fruit pulp into ice cream products can effectively mask the acidity from probiotic metabolism (Öztürk *et al*. 2018). In another study, sensory acceptability was significantly ($P < 0.05$) dropped in probiotic-enriched (with monocultures of *L. acidophilus*, *B. lactis* or their co-cultures) creamy goat cheese with the addition of 8% inulin during 21 days of refrigerated storage (7 ± 1°C). The colour, aroma, texture and overall acceptability assessments did not significantly differ between probiotic strains on day 21. However, cheese with monocultures of either *L. acidophilus* or *B. lactis* received higher flavour scores, 6.73 and 7.05 (out of 9), respectively, than control (without these probiotics) and their co-cultured samples, which were 6.01 and 5.68 respectively. The co-culturing of *Lactobacillus* and *Bifidobacterium* species may accelerate the accumulation of bitter, acetic and acidic flavours, reducing the flavour score in co-cultured cheese (Barbosa *et al*. 2016).

Only a few studies indicated that incorporating *Lactobacilli* and *Bifidobacterium* species in sheep milk cheese could promote the level of proteolysis and lipolysis favourably and subsequently enhance the sensory properties (Corbo *et al*. 2001; Santillo *et al*. 2009). The sensory evaluation of Argentinean soft sheep milk cheeses enriched with *L. acidophilus* LA-5 and *B. lactis* BB-12 resulted in promising results: a significantly higher appearance, elasticity and mouthfeel than their counterparts without these probiotics after 30 days of storage (Cuffia *et al*. 2018). In another study, sensory differences were observed in probiotic yoghurt made with cow and sheep milk. Cow milk yoghurt presented significantly low rating for appearance, consistency, overall impression and purchase intention than probiotic yoghurt made with mixed milk in any ratio and sheep milk yoghurt. The involvement of ewe milk improved the probiotic yoghurt's sensory characteristics and purchase intention (Vianna *et al*. 2017). The temperature in heat pretreatment of milk can also significantly alter the sensory property in classic and probiotic sheep yoghurt. Nonstandard heat treatments (60°C for 5 min) negatively influenced the appearance score due to the pronounced syneresis rate that gave the yoghurt a softer consistency which further impacted the overall acceptance in classic and probiotic-enriched sheep yoghurt compared to standard heat-treated (95°C for 5 min) samples. However, adding the probiotic strain, *L. rhamnosus* GG, did not negatively impact the sensory perspective in this study (Zamberlin and Samaržija 2017).

The sensory differences between fermented camel milk cultured with *L. acidophilus* and mixed culture of *L. acidophilus* and *B. lactis* were statistically nonsignificant ($P > 0.05$). However, in this experiment, the addition of 6% of inulin showed higher scores in flavour, consistency, acidity and appearance, reflecting higher overall scores than the control sample without inulin addition. Inulin rich in nutrients and flavour compounds supports probiotic growth contributing to higher sensory acceptance in fermented camel milk products (Ibrahim and Khalifa 2013). Similar

Table 3 Recent studies on sensory characteristics of probiotic-enriched nonbovine milk products

Type of milk	Product type	Product	Probiotic strain	Sensory acceptability	Remarks on sensory evaluation	Reference
Goat	Cheese	Probiotic Brazilian semihard Colho cheese	*L. acidophilus* LA-5 *L. casei* 01 *B. lactis* BB-12	• Lowest scores of appearance, flavour, taste, texture and general perception were found in standard cheese. • Appearance, colour and flavour were statistically nonsignificant between different probiotic strains applied. • Sample with 3 strains mixed culture appeared in higher general perception than monoculture samples and control	• Mixed probiotic culture was mostly preferred to monoculture, and control received lowest value in preference test. • *L. casei* 01 and mixed culture obtained with higher purchase intention where the purchase intention increased with the storage period in LA-5 and BB-12	Oliveira *et al*. (2012)
		Probiotic traditional semihard goat cheese	*L. acidophilus* *B. lactis*	• Probiotic-enriched cheese showed higher firmness than reference cheese which varied from 4.2–6.8, and the consistency varied from 4.1–5.9. • The flavour was varied among probiotic cheese samples but presented minor difference in reference cheese	• The addition of milk hydrolysate did not influence the texture or flavour of cheese. • Higher contents of PTA SN and free amino acids improved the flavour aspect of probiotic cheese	Gomes and Malcata (1998)
		Probiotic-enriched creamy goat cheese	*L. acidophilus* LA-5 *B. lactis* BB-12 LA-5 and BB-12 co-culture	• All sensory profiles dropped significantly during storage. • Samples with monoculture probiotic enrichment received higher flavour scores than control and co-cultured samples	• Co-culturing of Lactobacillus and Bifidobacterium species may promote the accumulation of bitter, acetic and acidic flavours, and hence, adversely impact flavour attribute	Barbosa *et al*. (2016)
	Yoghurt	Bio-yoghurt made from goat milk with/without addition of cysteine (0.5%)	*L. acidophilus* *L. casei* *B. lactis* BB-12	• Regular goat yoghurt received higher sensory score than bio-yoghurt at the beginning of storage main due to the intensive flavour production and better consistency. • After 14 days of storage, the acidification of regular yoghurt decreased the sensory scores compared to bio-yoghurt. • The addition of cysteine improved the organoleptic characteristics in both regular and bio-yoghurt	• Addition of cysteine correlated with the enhancement of acetaldehyde content and acidity production, which increases the sensory score. • The fermentation temperature showed minor impact on sensory properties, and 37°C received slightly lower scores than 42°C	Güler-Akın and Akın (2007)

(continued)

Table 3 (Continued).

Type of milk	Product type	Product	Probiotic strain	Sensory acceptability	Remarks on sensory evaluation	Reference
Goat	Yoghurt	Probiotic goat yoghurt with addition of fruit juice	*L. acidophilus* LA-5 *B. lactis* BB-12 *P. jensenii* 702	• Fruit yoghurt presented in significantly higher score in body, texture, taste and overall acceptability than plain yoghurt. • Colour, appearance and aroma showed no significant difference between fruit and plain yoghurt	• The addition of fruit juice improves the overall sensory property in probiotic goat yoghurt, with 10% as optimal • The sensory improvement is possibly contributed by the presence of flavour compounds in fruit juice and the probiotic metabolism	Ranadheera *et al.* (2012b)
		Probiotic goat yoghurt with stringless bee honey	*L. acidophilus* LA-5	• Appearance, colour, aroma and consistency were consistent in plain and honey-added yoghurt (regardless of the % addition). • Flavour, overall perception and purchase intention increased with the % of honey addition	• 10% and 15% honey addition were the most preferred and plain was least preferred. • Honey can render adverse sensorial perceptions from goat yoghurt	Machado *et al.* (2017)
	Fermented goat milk	Probiotic chocolate goat dairy beverage with inulin combined with oligofructose and goat cheese whey	*B. lactis*	• Formulation with whey and prebiotics at maximum concentration. Showed highest aroma and flavour scores than other formulations. • Flavour attributes varied from 4 to 6, and formulation with 45/100 mL of whey addition receives lowest score. • Appearance attributes varied from 6 to 7, and formulation with 45/100 mL of whey addition receives lowest score. • Texture attribute was not affected by the addition of whey and prebiotics	• Combination of cheese whey in probiotic fermented goat milk positively influences the flavour and aroma attributes. • Increased whey content subsequently improves the flavour attribute in sensory perception	da Silveira *et al.* (2015)
		Fermented goat milk drinks from co-cultured probiotics	*L. acidophilus* LA-5 *B. lactis* BB-12 *P. jensenii* 702	• The sensory characteristics of all samples in this study showed statistically nonsignificant differences. • Sensory scores were generally decreased with the storage period, from fresh to 3 weeks storage	• Co-culturing of LA-5 and BB-12 and LA-5 and BB-12 and 702 presented slightly higher overall acceptability than other samples	Ranadheera *et al.* (2016)
	Ice cream	Probiotic goat ice cream with addition of white/ blue Myrtus fruit pulp	*L. casei* 431	• No difference was obtained in texture and consistency scores in all samples. • Blue fruit added sample showed highest colour and appearance score. • White fruit added sample showed highest taste and flavour attributes, whereas the lowest taste score was obtained in probiotic-only sample	• Decreased taste score in probiotic-only sample is potentially due to the pH drop after fermentation negatively affecting the flavour and taste. • The addition of fruit pulp improves the taste of the ice cream and masks the sour taste	Öztürk *et al.* (2018)

(continued)

Table 3 (Continued).

Type of milk	Product type	Product	Probiotic strain	Sensory acceptability	Remarks on sensory evaluation	Reference
Sheep	Cheese	Ewe's milk Feta cheese with fruit pieces immobilised *L. casei*	*L. casei* ATCC 393	• Commercial Feta indicated a pronounced sour taste than probiotic Feta. • A fruity note was observed in fruit pieces immobilised probiotic incorporated Feta. • No significant difference in cheese flavour between *L. casei*-enriched and regular Feta cheese	• Fruit pieces immobilised probiotic enrichment in ewe's milk Feta cheese provided a distinctive taste without sacrificing other sensory attributes	Kourkoutas *et al.* (2006)
		Ewe's milk Canestrato Pugliese hard cheese with incorporation of *Bifidobacterium*	*B. bifidum* BB-02 *B. longum* BB-46	• No significant difference was observed in all evaluated sensory attributes including appearance, colour, mechanical characteristics, smell, taste and texture. • All samples were described as having small, uniformly distributed eyes, pale yellow colour, elastic consistency, pronounced Pecorino-like smell and very salty taste and tended to be moderately piquant	• The incorporation of *Bifidobacterium* did not alter the main feature of Canestrato Pugliese hard cheese	Corbo *et al.* (2001)
		Probiotic Scamorza ewe's milk cheese	Mix of *B. longum* BL-46 and *B. lactis* BB-12 *L. acidophilus* LA-5	• Seasoned attribute was affected by probiotic strains; mixed *Bifidobacterium* species were presented in significantly lower seasoned taste than control and LA-5. • Some appearance attributes were differentiated between control and probiotic cheese, S-BB and S-LA cheeses appeared in higher colour uniformity than control, and control presented higher yellowness. • From texture perspective, control cheese was less grainy and creamy than S-BB and S-LA, and lower friability and adhesivity were observed in S-BB and S-LA	• Bifidobacterium species may be able to produce particular metabolites which affect 'seasoned' attribute, and L. acidophilus was absent in producing this type of metabolites. • Probiotic incorporation may influence the acidification of cheese which further relates to texture modification	Albenzio *et al.* (2013)

(continued)

Table 3 (Continued).

Type of milk	Product type	Product	Probiotic strain	Sensory acceptability	Remarks on sensory evaluation	Reference
		Probiotic soft sheep's cheese	*L. acidophilus* LA-5 *B. lactis* BB-12	• Probiotic enrichment did not influence the sensory attributes of odour, colour, cream flavour, residual flavour, salty, bitter and acid taste. • Probiotic cheese samples presented significantly higher score of appearance of mass, elasticity and mouthfeel	• Probiotic-enriched soft sheep cheese can be considered as an acceptable probiotic carrier with sufficient probiotic viability and good sensory acceptance	Cuffia *et al.* (2018)
Sheep	Yoghurt	Probiotic sheep milk yoghurt treated with different heating temperatures	*L. rhamnosus* GG	• Heating temperature did not significantly alter the colour, taste and aroma of probiotic yoghurt. • Nonstandard heating temperature (60°C/5 min) gives lower scores of appearance and consistency. • Probiotic-incorporated sheep yoghurt presented higher sensory scores than classical yoghurt	• Lower heating temperature treatment of milk results in pronounced syneresis which decreases the appearance and consistency in yoghurt • Probiotic strain *L. rhamnosus* GG did not have adverse impact on the consistency of the nonstandard heat-treated probiotic yoghurts	Zamberlin and Samaržija (2017)
		Probiotic yoghurt with a mixture of cow and sheep milk	*L. acidophilus* LA-5	• Solely cow yoghurt presented lowest consistency, overall impression and purchase intention, whereas samples with other ratios were statistically nonsignificant in these attributes. • Solely cow yoghurt and sheep yoghurt were found in similar appearance score which was lower than mixed milk yoghurt. • Aroma and flavour attributes were not differentiated in all samples	• Lower firmness and higher spontaneous syneresis are main contributors to low acceptance in sole cow yoghurt. • The addition of ewe milk improved the sensory characteristics and purchase intention of probiotic yoghurt	Vianna *et al.* (2017)
Camel	Yoghurt	Probiotic camel yoghurt with *Cinnamomum verum* and *Allium sativum* extract	*L. acidophilus* LA-5 *B. lactis* BB-12 *L. casei* LC-01	• No difference was observed in aroma, bitterness and overall preference scores from probiotic-enriched camel milk with/without the addition of extracts. • The presence of *A. sativum* and *C. verum* increased the sweetness score and decreased the sourness score	• The deodorisation effect of milk is able to mask the AMS (allyl methyl sulphide) in terms of the 'garlic odour'	Shori and Baba (2015)

(continued)

Table 3 (Continued).

Type of milk	Product type	Product	Probiotic strain	Sensory acceptability	Remarks on sensory evaluation	Reference
	Frozen yoghurt	Probiotic frozen yoghurt made from camel and bovine milk	*B. infantis* DSM 20088 *B. angulatum* DSM 20098	• Flavour score of bovine milk frozen yoghurt was significantly higher than camel milk. • No significant difference was observed in softness, colour and vanillin odour	• The unpleasant odour in camel milk was identified as the most obvious drawback of its frozen yoghurt product	AL-Saleh *et al.* (2011)
	Fermented milk	Probiotic fermented camel milk with addition of inulin	*L. acidophilus* DSMZ 20079 *B. bifidum* DSMZ 20082	• No significant difference in sensory characteristics was detected in all fermented camel milk samples when fresh. • No significant difference from sensory perspective was obtained in *L. acidophilus*, *L. acidophilus* and *B. bifidum* mixed samples. • Flavour, consistency, acidity and appearance scores were significantly higher followed by the increased addition of inulin up to 6% after 14 days of storage	• The probiotic strains did not influence the sensory characteristics in fermented camel milk. • 6% of inulin addition was determined as the most acceptable ratio from the sensory perspective	Ibrahim and Khalifa (2013)
Camel		Probiotic fermented camel milk from selected bacterial starter cultures	*L. acidophilus* *L. lactis*	• The colour was not influenced by probiotic strains. • *L. acidophilus*-fermented camel milk presented in higher score in smell, consistency, taste and overall acceptability than *L. lactis*	• *L. acidophilus* was suggested to be more suitable for fermented camel milk products	Rahman *et al.* (2009)
Buffalo	Cheese	Probiotic buffalo milk Ricotta cheese	*L. acidophilus* LA-5	• Panellists observed no significant difference on day 0 between classical and probiotic buffalo Ricotta cheese samples. • Panellists characterised that both cheeses appeared in white, shiny, consistent in terms of colour, uniform in terms of appearance and flat flavour with low buttery, low acidic and cheddar whey score. • The overall acceptability score of probiotic Ricotta cheese remained constant until 4th day of storage, where after 4th day, the score decreased significantly	• Probiotic Ricotta cheese can be considered a good probiotic carrier for *L. acidophilus* LA-5 with acceptable sensory characteristics	Sameer *et al.* (2020)

(continued)

Table 3 (Continued).

Type of milk	Product type	Product	Probiotic strain	Sensory acceptability	Remarks on sensory evaluation	Reference
		Minas-type fresh cheese made with buffalo milk probiotic culture with the addition of lactic acid	*L. acidophilus* LA-5	• Texture, taste and overall acceptability did not differ regardless of the addition of probiotic culture or lactic acid. • Aroma was detected in higher score with the addition of lactic acid, but not influenced by probiotic enrichment	• The addition of *L. acidophilus* LA-5 did not influence the sensory characteristics in buffalo Minas-type fresh cheese	(Marcatti *et al*. 2009)
	Yoghurt	Probiotic *dahi* and yoghurt made from buffalo milk	*B. bifidum* I *L. acidophilus* R	• Probiotic *dahi* exhibited in lower flavour score which subsequently reduced the overall score than classical *dahi*. • No significant difference in overall score was observed between regular yoghurt and probiotic yoghurt	• Lower flavour score in probiotic *dahi* is potentially due to the higher acidification masked by the original flavour of *dahi*. • Fortification of *B. bifidum* I and *L. acidophilus* R did not alter the sensory characteristics of buffalo yoghurt	Vijayendra and Gupta (2012)
Buffalo	Yoghurt	Symbiotic yoghurt of buffalo milk	*L. acidophilus* *B. bifidum*	• Higher taste score was observed in probiotic-enriched prebiotic-free samples, and sample with *B. bifidum* presented higher taste score than *L. acidophilus*. • Sample with *L. acidophilus* appeared with highest texture score, and mix-cultured samples received lower texture score than monoculture. • The overall acceptability score was greater in monocultured probiotic samples rather than mix-cultured samples, and the natural yoghurt got higher score than symbiotic yoghurt	• Buffalo milk fermented with sole probiotic strain showed better sensory properties than mixed-culture, and the addition of prebiotics relatively reduced the sensory score	Ehsani *et al*. (2016)
	Fermented milk	Flavoured probiotic buffalo milk (mango, pineapple and strawberry)	*L. acidophilus*	Colour, flavour and overall acceptability did not differ between three flavours at day 1. The score of all attributes decreased after 6 days of storage. Pineapple flavour showed relatively lower flavour and overall acceptability score than the other two flavours at day 6	Flavoured probiotic buffalo milk presented high overall acceptability	Junaid *et al*. (2013)

(continued)

Table 3 (Continued).

Type of milk	Product type	Product	Probiotic strain	Sensory acceptability	Remarks on sensory evaluation	Reference
Donkey	Fermented milk	Probiotic fermented donkey milk	*L. acidophilus* *L. casei*	The sensory attributes of overall acceptability, colour, odour and appearance did not differ between control and probiotic fermented donkey milk. Probiotic enriched sample showed higher taste score than control	Higher taste score was potentially contributed by the greater acidification and flavour production from probiotic metabolism, which indicates that probiotics are susceptible to produce fermented donkey milk	Perna *et al*. (2015)
		Fermented donkey milk beverage with *Lactobacilli*	*L. rhamnosus* AT 194 *L. rhamnosus* CLT 2/2 *L. casei* LC 88	• Visual characteristics and basic tastes were not differentiated between three probiotic strains. • For odour, AT 194 presented in pronounced ‘acidified lactic’ and ‘boiled vegetables’ smell, CLT 2/2 received higher ‘grassy’ and ‘cow-herd’ score and LC 88 generally obtained intermedium score. • Aroma descriptors were mostly nonsignificantly different, except greater ‘boiled vegetables’ aroma was detected in AT 194 followed by CLT 2/2 and LC 88. • The pleasantness under trigeminal sensations category showed higher score in AC 194, followed by CLT 2/2 and LC 88	• Generally, *L. casei* was more susceptible to producing fermented donkey beverages due to more balanced olfactory profile from individual descriptors. • However, *L. rhamnosus* AT 194 was mostly preferred under organoleptic perspective	Chiavari *et al*. (2005)

(continued)

Table 3 (Continued).

Type of milk	Product type	Product	Probiotic strain	Sensory acceptability	Remarks on sensory evaluation	Reference
Donkey	Fermented milk	Probiotic fermented donkey milk	*L. plantarum* Lp5 *L. plantarum* Lp7 *L. plantarum* Lp27 *L. plantarum* Lp43	• For appearance, Lp27 received highest serum separation value than other three strains, and colour did not differ between strains. • For aroma, Lp7 exhibited in highest aroma intensity and acid score, whereas Lp27 showed the lowest. • For flavour, Lp7 and Lp43 presented in higher fermented milk flavour, Lp7 also received significantly higher score of acid flavour, and sweet, metallic and salty did not differ. • For texture, viscosity did not differ between strains, where Lp27 showed lowest overall score, and difference in other three strains was statistically nonsignificant	• Lp7 got highest overall score, which corresponded with the higher aroma and milk flavour intensity, whereas lowest overall score for Lp43 may due to the bland flavour	(Turchi *et al*. 2017)

descriptive sensory scores were obtained in buffalo Ricotta cheese made using the traditional method and probiotic *L. acidophilus* La-5-formulated method. A high overall likeness was obtained in both samples (8.8 and 9.0 out of 10 scales, respectively), which indicated that probiotic enrichment did not negatively influence the sensory profile in buffalo Ricotta cheese (Sameer *et al*. 2020). Compared with conventional donkey milk yoghurt, *L. acidophilus*- and *L. casei*-enriched donkey milk yoghurt appeared in similar sensory profiles and good overall acceptability (7.11 for traditional and 7.02 for probiotic yoghurt). A higher rating for taste was observed in probiotic donkey yoghurt (7.32) than in the conventional product (6.51) possibly due to the production of flavour components from probiotic metabolism (Perna *et al*. 2015). Donkey milk fermented with three probiotic strains (*L. rhamnosus* AT 194, CLT 2/2 and *L. casei* LC 88) presented similar visual characteristics (colour, homogeneity and grittiness) and basic tastes (sweet, salty, bitterness and acid). The aroma and trigeminal sensations were also not significantly varied except for a higher boiled vegetable aroma detection in AT 194 (4.88), followed by CLT 2/2 (2.86) and LC 88 (2.18). AT 194 also gave higher pleasantness (5.11) than the other two strains (2.96 and 2.17, respectively). The odour profiles were significantly varied between strains as well. Overall, *L. casei* was fund to be the most capable strain to produce fermented donkey milk beverages due to a more balanced olfactory profile (Chiavari *et al*. 2005).

Safety aspects of probiotic-enriched nonbovine milk products

The uniqueness of probiotics in food production is that they are living organisms when administered, which acquires the capability of potential infectivity and *in situ* toxin production (Sanders *et al*. 2010). Theoretically, with antibiotic-resistance genes in certain probiotic species, a potential risk of transferring these genes into the other microbiota in the gut microbiome can exist. Therefore, the genetic stability, pernicious metabolic activities, pathogenicity and immunological effects of the specific probiotic species and strains should be comprehensively assessed before production (Sanders *et al*. 2010).

The isolated probiotics from nonbovine milk products are considered safe and harmless for consumption. Safety properties, including DNAse activity, biogenic amine production and antibiotic resistance, were evaluated in probiotic isolates (*L. plantarum* and *L. paracasei*) from farmhouse probiotic goat cheese. All strains were considered safe to consume (Lavilla-Lerma *et al*. 2013). In a study by Gotteland *et al*., 421 strains of *Lactobacillus* isolated from plants, artisanal goat cheese, human stools and breast milk were evaluated for their safety characteristics via animal studies. In this study, a strain of *L. rhamnosus* QF60-2 from goat cheese was discarded due to the potential of bacterial translocation in the liver during animal studies (Gotteland *et al*. 2014). Safety evaluation of haemolytic activity and antibiotic susceptibility were carried out in autochthonous *Lactobacillus* isolates from traditional sheep cheese. No effect was observed in the haemolytic evaluation, and selected strains exhibited susceptibility to 7 out of 10 common antibiotics (Mangia *et al*. 2019). Similarly, the safety performances of antibiotic susceptibility, biochemical and haemolytic activity and biogenic amine production were evaluated in *Lactiplantibacillus plantarum* strains isolated from Slovak ovine and caprine cheeses. They concluded that certain strains were harmless, safe and possessed probiotic properties and hence can be included as starter cultures and starter adjuncts in commercial applications (Bujnakova and Strakova 2017). The safety aspects of lactic acid bacteria isolated from Iranian traditional fermented camel milk (Chal) indicated that all strains accommodated at least two or more virulent genes where cylB, gelE and efaAfs were most frequently detected. No β-haemolysis was observed in all strains, while most were resistant to polymyxin B and kanamycin. Further, *L. paraplantarum*, *L. kefiri*, *L. paracasei*, *L. plantarum* and *Weissella cibaria* presented resistance to vancomycin and kanamycin (Soleymanzadeh *et al*. 2017). Similar results were obtained in *L. casei* and *L. fermentum* strains from water-buffalo Mozzarella cheese. Most strains were resistant to kanamycin, and all were resistant to vancomycin. *L. fermentum* SJRP43 notably received less virulent genes and antibiotic resistance (de Souza *et al*. 2019).

Limitations and opportunities

Probiotic-incorporated nonbovine milk products have multiple limitations and challenges compared to bovine milk. For instance, some nonbovine milk, such as camel and donkey milk, lack versatility compared to bovine milk due to the absence or low content of kappa casein (?-CN) which reduces their coagulation capability (Berhe *et al*. 2017). Therefore, camel milk and donkey milk are rarely used for cheese production. In addition, camel milk's antibacterial characteristic makes it difficult to ferment, where the low acidification further leads to weak protein structure and soft consistency, making it unsuitable for producing yoghurt-type products (Berhe *et al*. 2018). In goat milk, high content of short-chain and medium-chain free fatty acids was associated with 'goaty' flavour/objectionable rancid flavour in goat milk products (Park *et al*. 2006). The productivity and total production of nonbovine milk remain very low compared to cow milk, as bovine milk contributes to ~80% of global dairy production (FAO 2020).

Further, the yield of nonbovine milk production is also lower than cow milk (Tsakalidou and Papadimitriou 2016). Most of the nonbovine dairy farming systems remained in downward mobility. They relied on traditional management techniques such as the absence of feeding supplementation, natural reproduction and hand-milking operations (Faye and Konuspayeva 2012). Particular nondairy milk and dairy products are only available locally (Tsakalidou and Papadimitriou 2016). Mostly, dairy camel farming is mainly concentrated in remote places with extensive management systems. Thus, camel milk is traditionally not sold and is only used for self-consumption in certain regions (Faye 2013). However, in recent years, the modernisation of dairy camel farming was gradually implemented, which introduced milking machines, scientific reproduction techniques, feed supplementations and industrial milk process systems (Nagy and Juhasz 2016). Since nonbovine milk is generally produced from remote regions, the issues such as transportation, storage and processing made the nonbovine milk products relatively isolated from the international market. Therefore, the market integration of nonbovine milk products with or without probiotics still needs to be developed (Tsakalidou and Papadimitriou 2016).

However, with more comprehensive studies on probiotic-enriched nonbovine milk products, beneficial and functional characteristics are gradually better understood. For example, past studies showed that some consumers who showed allergic reactions to cow milk may be able to consume nonbovine milk (e.g. goat and sheep) as a substitute (Pina *et al*. 2003). However, this warrants further research as the use of nonbovine milk in the prevention of cow milk allergy is yet to be thoroughly analysed. With the increased interest in the functional benefits of probiotic-incorporated food products, probiotic-enriched nonbovine milk products have been getting more attention in recent years (Ranadheera *et al*. 2018). In addition, there have been some well-developed probiotic-enriched nonbovine milk products such as goat/sheep and buffalo milk cheese with high consumer acceptability. Therefore, probiotic-enriched nonbovine milk products are clearly one of the major future trends in functional food development.

CONCLUSION

The products from probiotic-enriched nonbovine milk are technically diverse and include cheese, yoghurt, fermented milk, frozen yoghurt and ice cream. Probiotic viability in most of these products was highly satisfactory during storage. However, most of these studies were conducted on a laboratory scale and using *in vitro* assays. Hence, the potential for industrial-scale production needs further *in vivo* research to verify the same effects shown *in vitro*. The probiotic performance during gastric and intestinal adhesion suggested that nonbovine milk can adequately deliver live probiotics into the targeted area in the gut in reasonable numbers. Most of these studies indicated a strain-dependent property, and some researchers suggested that adding certain adjuncts or additives (e.g. prebiotics) may provide extra protection for probiotics. Physiochemical and quality parameters of these products primarily depended on the type of milk used. They were also partially influenced by probiotic strains and the addition of other ingredients. From a sensory perspective, probiotics generally showed no effect on sensory characteristics. However, the overall sensory acceptance of these products remained low mainly due to the chemical or compositional features in nonbovine milk, such as short-chain fatty acids in goat milk creating a 'goaty' flavour in goat milk products. Probiotic-enriched nonbovine milk products can be generally considered safe to consume. However, some isolated probiotic strains in these products were detected with a certain level of antibiotic resistance and with the presence of virulent genes. The concerns of the limitation of these products are mainly focused on lack of productivity, relatively extensive farming methods and low market integration. However, the health benefits of probiotics and the diverse functionality of nonbovine milk products compared to cow milk provide a promising potential for developing these products within the functional food industry.

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AUTHOR CONTRIBUTIONS

Wang Shi: Writing – original draft. **Nenad Naumovski:** Writing – review and editing. **Said Ajlouni:** Writing – review and editing. **Mutamed Ayyash:** Writing – review and editing. **Ramon Silva:** Writing – original draft; writing – review and editing. **Celso Fasura Balthazar:** Conceptualization; methodology; writing – original draft; writing – review and editing. **Erick Almeida Esmerino:** Writing – original draft; writing – review and editing. **Monica Freitas:** Writing – original draft; writing – review and editing. **Marcia Cristina:** Writing – original draft; writing – review and editing. **Anderson S. Sant'Ana:** Conceptualization; methodology; resources; supervision; writing – review and editing. **Adriano Gomes:** Conceptualization; investigation; methodology; resources; supervision; writing – review and editing. **Senaka Ranadheera:** Conceptualization; investigation; methodology; resources; supervision; writing – review and editing.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no datasets were generated or analysed during the current study.

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