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Traditional Sri Lankan fermented buffalo (*Bubalus bubalis*) milk gel (*Meekiri*): technology, microbiology and quality characteristics

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Abstract

Meekiri (sometimes also known as *Mee-Deekiri*); fermented buffalo milk gel is a deep-rooted dairy product in Sri Lankan food culture and the production of *Meekiri* plays an integral part in the livelihood of rural farming. *Meekiri* consumption is widespread irrespective of geographic boundaries, across the cultural and/or ethnic communities. In Sri Lanka, buffalo milk is predominantly used in producing *Meekiri*, where production has been specialized in various geographic areas in the country, associated with major buffalo farming regions. Physicochemical and microbiological quality attributes are apparent to differ in *Meekiri* according to varying production regions, processing techniques and storage conditions. The mouthfeel and taste of *Meekiri* are widely accepted to be thicker and creamier with a pleasant note and is whiter in colour compared to fermented cow milk gel/yoghurt. Since *Meekiri* production is localized in Sri Lanka and available as traditional know-how at the primary production level, up-to-date comprehensive scientific literature that accounts for processing and detailed product quality characteristics is lacking. Hence, this review evaluates and outlines updated information about the *Meekiri* production, associated buffalo farming systems, quality characteristics of *Meekiri* including physicochemical, sensorial and microbiological aspects in the final product.

Keywords: Buffalo milk, Curd, Fermented dairy products, *Meekiri*, Mesophilic starter culture, Buffalo farming

Introduction

Buffalo farming in Sri Lanka is one of the vital livestock sectors, which is well integrated into the traditional livelihoods of rural dairy farmers. *Bubalus bubalis*, or commonly known as water buffalo, has been classified into two groups mainly the Swamp buffaloes of Southeast Asia and River buffaloes predominantly found in the Indian subcontinent [1]. The mainstream of buffalo milk produced in Sri Lanka is destined to produce fermented water buffalo's milk gel, which is commonly known as *Meekiri* or Curd, throughout the country. *Meekiri* is a unique fermented dairy product and ubiquitous processed buffalo milk-derived dairy food in Sri Lankan food culture. Fermentation of milk is one of the major preservation techniques to preserve the excess milk yield [2]. The origin of fermented milk is dated back to ancient civilizations and evolved with culinary skills along with the advances in keeping livestock and agricultural practices [3]. *Meekiri* has been an integral part of food since ancient times, where it has been used in royal cuisines too. According to famous folk tales (unwritten literature illustrating historical values of various aspects) on "Andare" (the legendary royal comedian in Sri Lanka), *Meekiri* has been considered as one of the best appealing and overwhelming desserts with a greater tempting. The concept associated with this folk tale is adopted as a general belief and is still applicable among consumers,

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where even if the person is satisfied with food, *Meekiri* is irresistible as a dessert.

Traditional fermented foods are playing a vital role in socio-economic and cultural development in local communities. Sri Lanka has long been renowned for its traditional foods and the "*Pasgorasa*" (five tastes of milk) was made of excess fresh milk included a combination of five items; (1) "*Ksheer*" (Sanskrit word for milk), (2) "*Deekiri*" (fermented cow milk), (3) "*Githel*" or "*Dunthel*" (Ghee, *Githel* made from cow milk & *Dunthel* made from buffalo milk), (4) "*Wendaru* or *Yodaya*" (cream), (5) "*Moru* or *Mohuru*" (whey). Moreover, there has been a traditional sweet Buddhist offering called "*Chatu Madura*" (the four delicacies) and it is an amalgamation of (1) ghee, (2) "*Wendaru*", (3) concentrated and solidified sugar cane syrup "Jaggery or *Hakuru*" [however, at present any type of jaggery is commonly used, which is often obtained by concentrated thick brown solid from coconut (*Cocos nucifera*) or kithul palm (*Caryota urens*) flower sap] and (4) bee honey [4] (Prof. Nimal Perera and Ven Nakulugamuwe Nimala thero, personal communications, 15 August 2021). Curd makes an unbeatable combination with kithul treacle. Kithul treacle is made from the sap collected from the inflorescence of the kithul palm, which is native to Sri Lanka. The sap is boiled down to dark brown syrup, thick and sweet in flavour, with resembling dates and a slight hint of caramel. This combination is often offered at Buddhist alms-giving ceremonies as a tradition, illustrating the importance of *Meekiri* in Sri Lankan food culture. Health benefits of such traditional foods can be passed into modern diets with proper interventions of modern food processing technologies [5], since food and health are directly related as detailed in Ayurvedic traditional methods of food habits and dietary preparations [6]. Fermented buffalo milk has been used as numerous indigenous beverages in Asia, e.g. *Dahi, Mohi, Dadih* [7–9] and in Sri Lanka, *Meekiri* has been dominated in the food culture [10]. *Meekiri* has been a traditional ethnic food for many years in Sri Lanka, although numerous competitive foods, e.g. Greek-style yoghurt, are emerging in the Sri Lankan market. *Meekiri* still holds its position as a dessert in Sri Lankan food culture, among the other popular dairy desserts, e.g. ice cream, across varying generations without a competition.

Meekiri is obtained by fermentation of buffalo milk using mesophilic bacterial cultures at room temperature, as an attempt to preserve the milk until consumption as well as a strategy for value-addition [11]. Sri Lankans are widely appreciating its thick consistency and characteristic taste as a local delicacy. In Sri Lankan food culture, consumption of *Meekiri* is dated back from ancient times and have been enjoying it as a dessert, breakfast as well as a snack [12]. *Meekiri* is associated with the cultural values of regional communities, where gifting a freshly made *Meekiri* in a clay pot wrapped in a woven coconut palm basket (Fig. 1A) is a common tradition in the southern part of Sri Lanka, which is believed to be the origin of *Meekiri*. Local production of *Meekiri* is a communal affair, where the members of the whole family participate in preparation, especially in heating the milk in a big vessel without letting it get the burnt taste. Traditional know-how passed through the generations and local specialities in the production of *Meekiri* are available in regions where *Meekiri* is predominantly produced in Sri Lanka. As a consequence of homemade bulk starter cultures or usage of previous day curd (e.g. back-slopping), an enormous variety of starter culture bacteria (e.g. lactic acid bacteria) consortium has resulted in products from different regional origins [10, 13]. Consequently, a wide array of product physicochemical properties has resulted. Investigating the hundred years old recipes in producing *Meekiri* and combining them with in-depth current knowledge is an essential key strategy in preserving the value of traditional ethnic buffalo milk-derived dairy products in Sri Lanka. Thus, detailed aspects of buffalo milk, the processing technology into *Meekiri* and its product quality characterization attributes are accounted for in this review.

Buffalo milk

Buffalo milk is unique compared to cow milk and contains a higher level of fat (6.7% vs. 3.7%), total protein (4.70% vs. 3.50%) and calcium (205 vs. 115, mg 100 mL^{-1}) content than that of cow milk, respectively [14]. Compared to cow milk, buffalo milk also has higher casein to protein ratio, a factor that is usually appreciated in producing stronger/firmer milk gels. Due to less water content (83.2% vs. 87.2%, respectively) and higher total solids (16.3% vs. 12.8%, respectively) than cow milk, buffalo milk is perceived to be thicker [14]. Visually, buffalo milk is relatively whiter than cow milk, due to a shortage in β-carotene [10], the pigment responsible for yellowness. As a consequence, *Meekiri* is also whiter in tone compared to fermented cow milk gel/cow milk curd, which is also referred to as "*Deekiri*" (Fig. 2). Buffalo milk contains higher peroxidase activity, and therefore, it has comparatively better natural preservative ability compared to cow milk [15]. The superior richness of constituents compared to cow milk makes buffalo milk a highly suitable and greatly demanded dairy product in Sri Lanka. Casein micelles, the primary structure of casein proteins and minerals in buffalo's milk, is highly mineralized and this resulted in higher mineral (calcium and phosphate) content in buffalo milk. Because of the higher mineral, fat and protein content in buffalo milk, its coagulation

Fig. 1 A woven basket from coconut palm fronds is the traditional method of transporting or gifting the *Meekiri* in Sri Lanka (**A**). This strategy provides a strong and rigid structure for transporting fragile clay pots without damaging the clay pot or destroying the structure of *Meekiri*. At present, *Meekiri* is commonly sold without woven coconut palm baskets in clay pots by stacking those together (**B**)

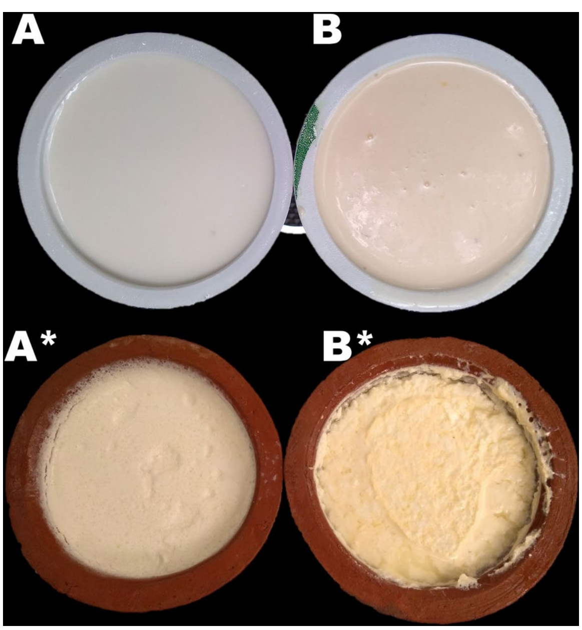


Fig. 2 Visual colour comparison of **A** *Meekiri* made of buffalo milk and **B** *Deekiri* (e.g. similar to common yoghurt) made of cow milk. *mark indicates the respective product in the clay pot. *Note*: Meekiri is comparatively whiter than *Deekiri* due to a shortage in β-carotene, the yellow pigment. Usually, the much thicker and creamier texture is also apparent in *Meekiri* as well

properties and milk gel characteristics are often superior compared to usual cow milk fermented gels [16].

Current status of the buffalo industry in Sri Lanka

Buffalo farming in Sri Lanka plays an important role in livestock production, and therefore, buffaloes are important contributors to the national dairy value chain/supply. The agriculture sector contributes about 7% of the national GDP of Sri Lanka [17], whereas the contribution of the livestock sector to the national GDP is around 0.8% [18]. Buffalo-keeping has been an integral part of the farming systems of Sri Lanka from an ancient time where the buffalo has been reared for multiple purposes including milk for producing *Meekiri*, manure and draft mainly for paddy cultivation [19, 20]. The current buffalo population in Sri Lanka is estimated at 0.47 million heads [21]. It is largely concentrated in the eastern (28%), southern (16%) and north-central (16%) provinces located in the dry and intermediate zones which collectively account for approximately 60% of the total buffalo population in the country [22]. A considerable proportion of buffalo farming in Sri Lanka is family level, and therefore, the production statistics are not well reflected, as those households often produce buffalo milk with the intention for consumption [23]. The variation in the buffalo population, milk production (buffalo and cow) in Sri Lanka over the last 10 years is shown in Fig. 3.

In 2019, the total annual milk production in Sri Lanka was just above 424 million litres and approximately 16% of this (67.5 million L) comprised of buffalo milk [21]. The highest buffalo milk production was coming from the eastern province (21 million L) followed by north-western (15.7 million L), north-central (13.2 million L) and southern (12.2 million L) provinces (Table 1). In Sri Lanka, the majority of the buffalo farmers rear buffaloes for draft power or as a source of ready cash, and therefore, a fewer number of buffaloes are kept for milking purposes [20]. Based on the statistics, it can be estimated that only 24% of the total buffalo population is being milked currently, suggesting that there is a huge potential exist for further expansion of the industry in terms of milk production although the majority of buffalo milk comes from smallholder herds [24].

Indigenous/local, Murrah, Nili-Ravi, Surti and their crosses are the predominant buffalo breeds found in Sri Lanka [19, 25]. The majority of the farmers rear local buffaloes with Murrah/Nili-Ravi crosses [19]. The proportion of local, pure-bred and cross-bred buffaloes were estimated at 69%, 6% and 25%, respectively [24]. Statistics suggest that there is a huge variation in average milk production per buffalo per annum (Table 1) depending on the type of animals kept, agro-ecology and systems of rearing. The highest productivity is observed in Kurunegala District (2103 L/buffalo/year), and the lowest was observed among Mannar, Rathnapura, Badulla and Kandy Districts (< 200 L of milk per buffalo per annum). It has been reported that the average production of milk from Murrah, Nili-Ravi and Surti breeds is about 1400–2000 kg, 1500–2000 kg and 1500–1800 kg, respectively, with 7–8% fat in lactation of 305 days [1, 25].

Buffalo production systems in Sri Lanka

Buffalo production systems in Sri Lanka can be classified according to the breed and husbandry practices, which are closely related to the agro-ecology and climatic factors [24]. Buffalo farm management and uses vary with the agro-ecology, rainfall and cropping patterns. In all these systems, productivity and reproductive performance are at sub-optimal levels [20, 26]. Major buffalo production systems in Sri Lanka and their characteristics are summarized in Table 2.

The utilization of buffaloes for milking has not been uniform within Sri Lanka. In some districts, e.g., Hambantota, Batticaloa, Polonnaruwa and Trincomalee, buffaloes were mainly reared as dairy animals, since long time ago. Nevertheless, at present, the same regions are still renowned for traditional *Meekiri* production. For example, "Tissa *Meekiri*" which is historically being prepared in the Tissamaharama area of the southern

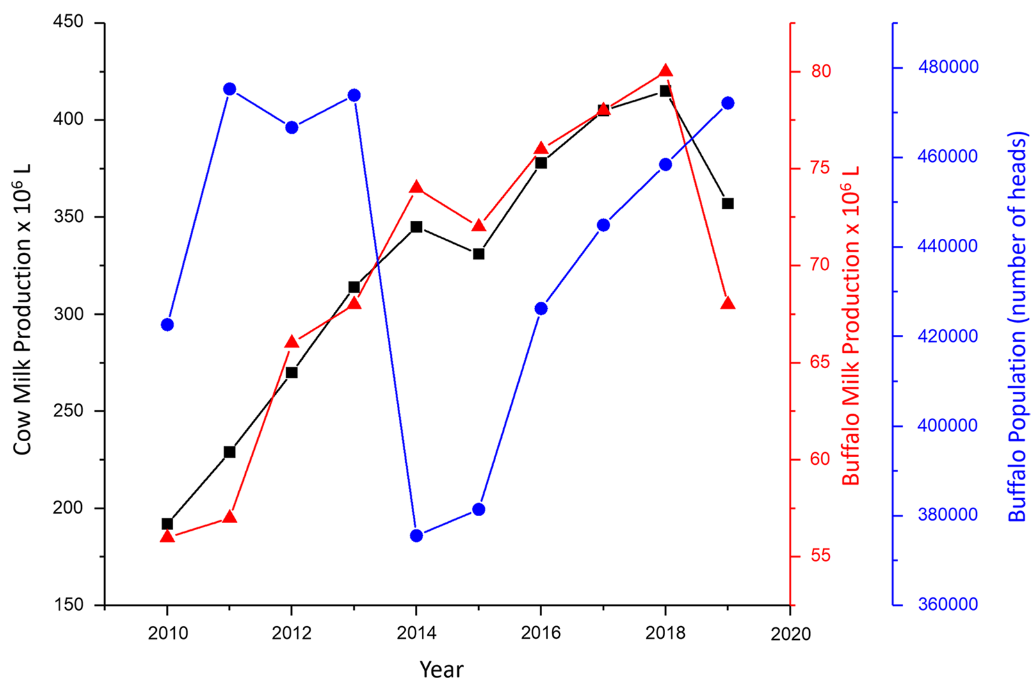


Fig. 3 Cow milk production (black), buffalo milk production (red) and buffalo population in Sri Lanka over the last decade (blue). A significant increase in the production of buffalo milk was reported in 2018/ 2019 compared to 2010. Total cow milk production was also reported as a similar trend (*Source:* Department of Census and Statistics, 2019)

Table 1 Distribution of the buffalo population, milking buffaloes and buffalo milk production (year 2017) in Sri Lanka

Province	District	No. of buffaloes	No. of milking buffaloes	Annual buffalo milk production (L)	Milk production per buffalo per year (L)[a]
Western	Colombo	7425	1794	1,370,443	763.9
	Gampaha	9977	2436	1,245,435	511.3
	Kalutara	18,508	4897	3,845,038	785.2
Central	Kandy	6113	1547	255,180	165.0
	Matale	7805	1874	498,847	266.2
	Nuwara Eliya	1531	201	76,736	381.8
Southern	Galle	11,698	2365	1,804,029	762.8
	Matara	9830	2647	2,004,029	757.1
	Hambantota	51,158	17,849	8,366,093	468.7
Northern	Jaffna	NA	NA	NA	NA
	Kilinochchi	2211	495	287,147	580.1
	Mannar	3168	498	62,048	124.6
	Vavuniya	4302	1047	423,300	404.3
	Mullathivu	6576	1,599	612,333	382.9
Eastern	Batticaloa	36,019	11,874	3,006,043	253.2
	Ampara	38,511	11,046	8,718,130	789.3
	Trincomalee	48,969	13,487	9,454,873	701.0
North-western	Kurunegala	25,608	6897	14,509,231	2103.7
	Puttalam	10,815	1584	1,160,622	732.7
North-central	Anuradhapura	45,175	12,658	7,830,858	618.6
	Polonnaruwa	26,480	7849	5,353,690	682.1
Uva	Badulla	4545	925	130,673	141.3
	Monaragala	51,443	15,614	6,617,871	423.8
Sabaragamuwa	Ratnapura	11,747	2425	311,799	128.6
	Kegalle	5298	757	144,188	190.5

Sources [21, 22]

NA data not available

[a] Estimated using annual buffalo milk production and number of milking buffaloes

[b] Provincial

province of the country is recognized as excellent quality and ideal *Meekiri* by general consumers, owing to traditional know-how and quality of the forages available in the area [27]. Free-grazing extensive system and semi-intensive systems of management are the most widely spread management systems in Sri Lanka in relation to buffalo farming. A semi-extensive buffalo farm and milking are illustrated in Fig. 4. Zero-supplementary feeding, absence of housing and free grazing are the main characteristics of extensive management systems [19, 26].

It has been reported that just over one-tenth of the country's buffalo population was utilized for milking [28]. Buffalo milk was thus mainly utilized for preparing *Meekiri* and *Dunthel* (ghee) and to a lesser extent for domestic consumption as fluid milk [29]. Traditional milking practices of buffaloes slightly differ from the modern milking practices in rural communities. In the past, the calves were separated from the milking buffaloes during the night and on the following day morning (preferably before 5.50 a.m.) they were milked. Short before starting to milk, the separated calf is allowed to suckle for a while to stimulate milk letdown process to facilitate easy and smooth milking. Thereafter, the calf was allowed to suckle freely throughout the day until it is separated during the night [27, 29].

Major *Meekiri* producing regions

In Sri Lanka, *Meekiri* production is largely associated with buffalo farming areas due to the "locally produced" concept or small-scale production at the household level, with no excess milk yield to sell or transport to another processing plant. *Meekiri* is a value-added product from buffalo milk, and therefore, farmers earn considerably higher profit by selling *Meekiri* instead of raw buffalo milk to another intermediate buyer or milk collector. At present, almost all buffalo farmers are producing *Meekiri*

Table 2 Buffalo production systems in Sri Lanka and their characteristics

Parameter	Production system				
	Dry-zone traditional village system	**Dry-zone irrigated settlement system**	**Intermediate zone/coconut triangle system**	**Wet-zone system**	**Peri-urban system**
Location	Districts in the north-central, northern, eastern, and parts of central, southern and north-western provinces	Areas coming under the irrigated settlements such as Mahaweli, Kirindi Oya, etc	Coconut triangle: intermediate and wet zone areas of north-western province and Gampaha district Intermediate Zone	Districts in the western and Sabaragamuwa provinces	Areas closer to the cities
Husbandry practices	Free grazing, or nomadic type large herds or small/medium-sized herds, allowed to graze on communal grazing lands during the day time and brought back home in the evening and kept in a paddock near the farmers' dwellings	Small herds are kept with a mixture of tethered grazing and feeding with cut grasses and fodder especially during night and cultivation season	Small herds, animals are allowed tethered-grazing under perennial plantations or along the roadsides	Small-holder mixed crop-livestock production system, zero-grazing, maintain in stall-fed conditions with heavy labour and service inputs for feed, health control, and artificial breeding	A specialized dairy production system not integrated with crops, animals are kept under confinement, all fodder and concentrates are purchased from outside
Popular breeds	Majority of the farmers rear local buffalo with Murrah/Nili-Ravi cross-breeds, > 50% of the herds in the eastern area having improved types	Cross-bred dairy-type animals	Local, Murrah, Nili-Ravi, Surti, and cross-breeds	Local and cross-bred Indian breeds, the proportion of improved buffaloes are slightly lower in lowlands	Local cross-breeds, Nili-Ravi and Murrah
Major management system	Extensive	Semi-intensive	Semi-intensive	Intensive	Intensive
Milk as a primary/secondary income source	Secondary	Primary	Primary	Primary or secondary depending on the locality	Primary
Milking practices	Limited milk extraction over a short lactation period, usually once a day milking	NA	Once/twice daily	NA	NA
Average milk yield (L per buffalo per day)	< 1 L for indigenous types and 1.5–2.7 L for cross-bred	2–5 L	5–6 L for pure-bred, 4–5 L for cross-bred, and 1 L for Local, average 3.1 L	~ 3–6 L	NA
Cost of production	Least cost	NA	Relatively high due to the high percentage of the cost for compound feed	Relatively high due to the high percentage of the cost for compound feed	NA
Herd size	1–250	NA	1–4 animals	2–3	NA

Sources: [19, 24–29]

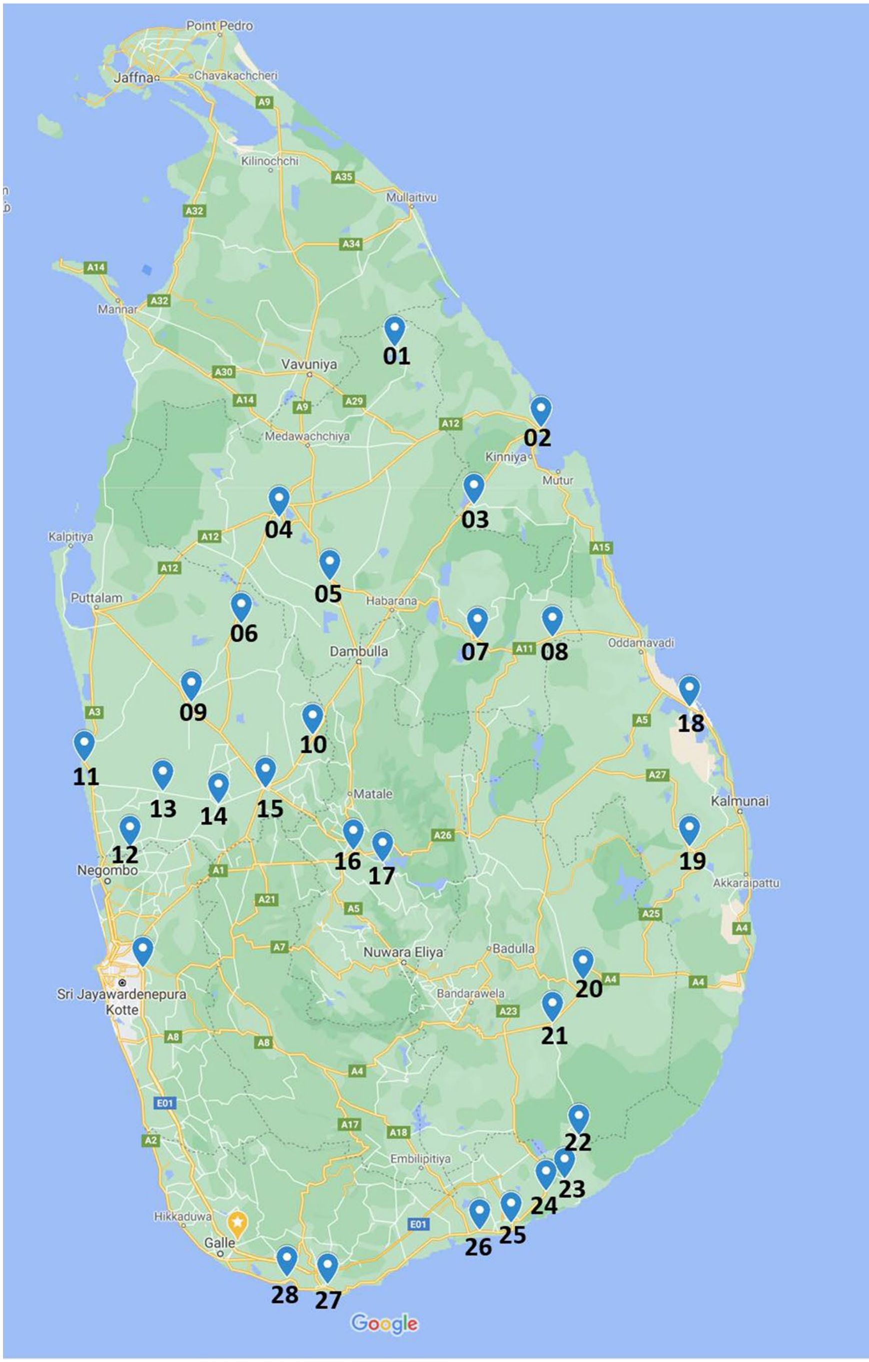
NA not available

Fig. 4 Milking a buffalo (**A**) from a semi-extensive buffalo farm (**B**) in Sri Lanka. Hand milking is commonly practised in both free-grazing extensive and semi-intensive systems of management. Similar to neat cattle production, usually clean and hygienic milking at an acceptable level is practised in buffalo farming as well

either at the household level or local community level or localized farm level, without being transported into a central processing plant. In Sri Lanka, however, specifically, there is no island-wide or large-scale buffalo milk collecting cold chain. This is mainly due to several reasons, i.e. (1) insufficient milk production for meeting the demand of large-scale and centralized *Meekiri* production; (2) not having excess raw milk yield to sell; (3) greater profit margin of selling *Meekiri* than raw milk to primary producers and (4) economic benefits of distributing/transporting final product instead of raw milk. However, from various geographic areas in Sri Lanka, few specific cases report the opposite. For example, about 92% of the buffalo farmers in the Thanamalwila area (Monaragala district) used to earn money by only selling raw buffalo milk and only 8% of the farmers are involved in the production of *Meekiri* [19]. In the peri-urban dairy production system in the Seethawakapura area (Western province), 13% of the farmers are involved in producing *Meekiri* [25]. In the coconut triangle (the area between Puttalam, Kurunegala and Colombo), buffalo milk is predominantly converted into *Meekiri,* since the local demand is high [24]. Because of all those reasons, major *Meekiri* production regions and buffalo farming areas are confounded. Some of the *Meekiri* production areas are well known and popular among consumers. Figure 5 shows such popular and major *Meekiri* production regions in Sri Lanka.

Production of *Meekiri*

Fresh buffalo milk is converted into *Meekiri*, through a microbial fermentation process, where fermentation is practised as a mode of preservation and extending the shelf-life of excess milk yield [30]. Even though various fermented buffalo milk products are available in the world, *Meekiri* is the sole and popular and commercially available fermented buffalo milk-derived product in Sri Lanka. Production of *Meekiri* involves several steps as shown in schematic illustration (Fig. 6). *Meekiri* production is an ancient art practised in Sri Lanka as a cottage industry for a long time. The majority of producers are manufacturing *Meekiri* using the milk obtained from their own herds. First, milk is boiled over an open fire (firewood was used for heat generation upon burning) for 20–30 min within 3 h from milking and then cooled to around 35–40 °C. The majority of the curd makers used aluminium vessels for milk collection and boiling. In the production process of *Meekiri*, the milk lactose is converted into lactic acid by the action of added starter culture's activity [2]. Starter cultures are added as freeze-dried pellets or commonly as a portion of mother culture maintaining at household-level or back-sloping inoculation from the previous day's production (referred to as *Muhun* in Sinhalese). This lactic acid production will reduce the milk pH, and at the isoelectric point of casein (pH 4.6), milk coagulation occurs [30]. At cottage level production of *Meekiri*, *Muhun* is added before the boiled milk is completely cooled to room temperature. These *Muhun* were obtained from previously prepared *Meekiri* (approximately 1 day old) based on producers evaluation of the best *Meekiri* quality. Therefore, continuously, *Muhun* is changing in accordance with the manufacturer's selection and maintenance. The temperature of the milk at the time when *Muhun* is added could be determined by experience. After inoculating with *Muhun*, the mixture is stirred firmly to distribute it evenly in the



No	Name of the site/location
01	PADAVIYA
02	TRINCOMALEE
03	KANTALE
04	ANURADHAPURA
05	MARADANKADAWALA
06	GALGAMUWA
07	POLONNARUWA
08	WELIKANDA
09	NIKAWERATIYA
10	MELSIRIPURA
11	CHILAW
12	SANDALANKAWA
13	KULIYAPITIYA
14	NARAMMALA
15	KURUNEGALA
16	KANDY
17	HARAGAMA
18	BATTICALOA
19	AMPARA
20	MONARAGALA
21	BUTTALA
22	KATARAGAMA
23	TISSAMAHARAMA
24	WEERAWILA
25	HAMBANTOTA
26	AMBALANTOTA
27	MATARA
28	WELIGAMA

Fig. 5 Major *Meekiri* producing sites/locations in Sri Lanka (Google maps). Sri Lanka is an island in the Indian Ocean, South-east of the Indian subcontinent between latitudes 5° and 10° N, and longitudes 79° and 82° E with a tropical warm climate. The rainfall pattern is mainly influenced by monsoon winds in the Indian Ocean. There is strong evidence of prehistoric human settlements in Sri Lanka dating back to approximately 125,000 BP

milk base. Usually, a spoon made of cleaned and polished coconut shells with a long wooden handle has been used. Then, the mix is poured into pre-washed and dried clay pots of equal size, which are left open and allowed to coagulate at room temperature (~30–35 °C). The minimum time required to achieve satisfactory curdling is 3–5 h from the inoculation which can be extended up to 36 h or even 72 h in some cases. It is finally sealed

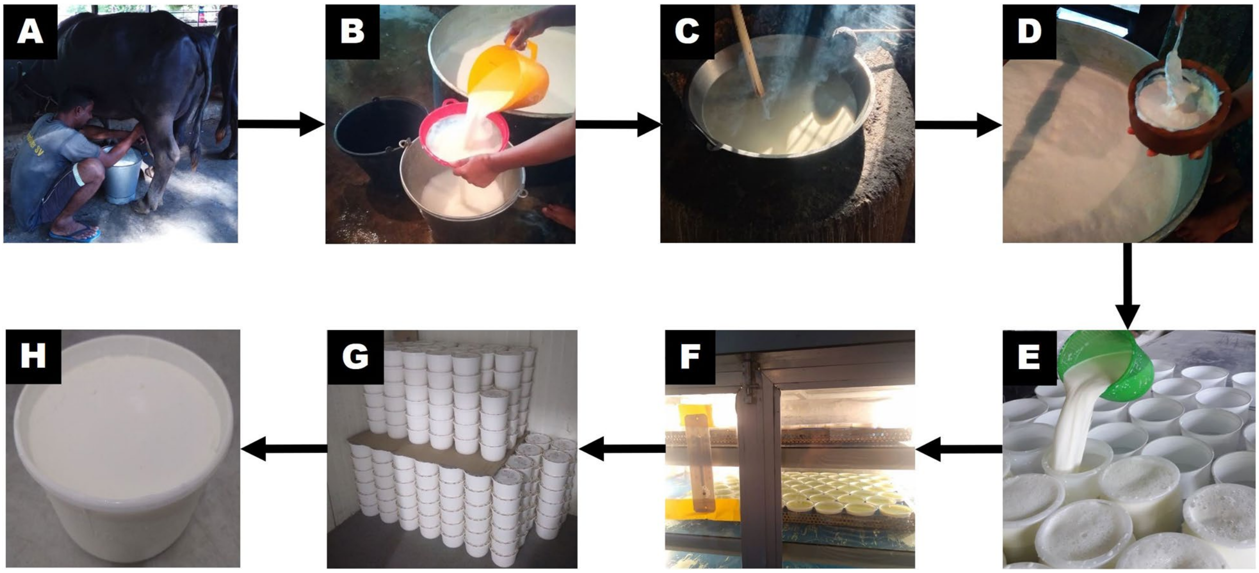


Fig. 6 Schematic illustration of steps involves in *Meekiri* production from buffalo milk. **A** Sourcing of raw milk; **B** staining of raw milk to remove extraneous materials; **C** heating of milk (boiling/20–30 min); **D** cooling to 35–40 °C (in traditional production, producers take few drops of milk on to their dorsal side of the hand and sense the temperature) and adding mesophilic starter culture; **E**: pour into consumer retail cups; **F**: incubation/fermentation (30–35 °C/12–14 h) until firm coagulum is formed; **G**: cooling; **H**: final product, *Meekiri*

by wrapping a piece of oil paper or natural banana leaf over the pot. The liquid that separates after the curd has formed is called whey or buttermilk (referred to as *Moru or Mohuru* in Sinhalese) and is considered a healthy drink that is consumed in the morning by certain villagers. Because of different processing parameters and conditions adopted at household production of *Meekiri*, coupled with undefined starter cultures and traditional practices, properties and quality of *Meekiri* are widely varied.

Storage, packaging and marketing

Traditionally, coagulation of buffalo milk is achieved in a clay pot and subsequently possible to store in a range of temperatures, mainly 4 °C (7 days of shelf-life) or ambient room temperature (1–3 days of shelf-life) until consumption [31]. At present, in Sri Lanka, the most popular packaging material for *Meekiri* is clay pots covered with paper or polythene cover. The use of low-density polyethylene (LDPE) cups and jars, however, is emerging as packaging material among some large-scale producers. Yet, the *Meekiri* packed in clay pots is highly preferred by the consumer, since *Meekiri* in plastic cups has impaired sensory properties, especially in terms of flavour and texture. Excess whey is absorbed by the clay pots and help to maintain product textural properties. Figure 7 illustrates the two common styles of storing and marketing of *Meekiri* in Sri Lanka. Clay pots, earthenware, contain a relatively high amount of iron oxide, as a result of firing them under direct heat and thus develop the characteristic brick-red colour, depending on the type of clay used as a raw material [32]. Firing contributes to food safety aspects of earthenware as well. Such clay pot is chemically inactive and does not react with the *Meekiri*. It is permeable to moisture and gasses, and therefore, shelf-life is limited. Compared to plastic containers, clay pots are heavy and easily broken, which is not widely appreciated along the distribution and supply chain. In contrast, the plastic packaging of *Meekiri* provides numerous benefits over the clay pots, such as its flexibility in moulding, easiness to print packaging and marketing information, lightweight, easiness in transportation, great durability, resistance to food chemicals and maintaining product consistency.

Physicochemical characteristics of *Meekiri*

The mean composition of *Meekiri* is varying, but it usually contains ~88% of water, 7–8% of fat, ~3.4% protein, ~5.2% lactose, ~0.14% calcium and ~0.09% phosphorus [16]. The physicochemical characteristics of organoleptically optimal *Meekiri* have a firm texture, pleasant aroma and glossy surface compared to the counter product (i.e. *Deekiri*; fermented cow's milk gel). *Meekiri* is creamy with a thick mouth-feel and higher viscosity and gives a sour taste. Also, *Meekiri* must be free from extraneous materials and free from dirt that could origin due to unhygienic practices at small scale non-standardized household production. The fermented gel

Fig. 7 Packaging and marketing alternatives, **A**, **A*** clay pot; **B**, **B*** low-density polyethylene (LDPE) cup (commonly referred to as plastic cups), respectively. Clay pots are permeable to moisture and gasses, and therefore, shelf-life is short compared to plastic packaging materials; however, in terms of favourable flavour and texture, consumers preferred buffalo curd stored in clay pots. This could be due to excess whey absorption by the clay pots resulting in better textural properties

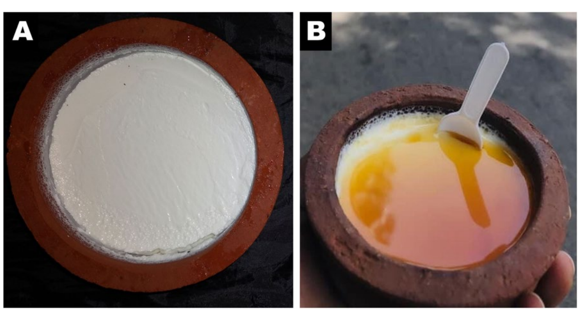


Fig. 8 The appearance of *Meekiri* from the top in a clay pot (**A**) and most common way of consuming *Meekiri*, with palm treacle: *kithul* (*Caryota urens*) *or* coconut (*Cocos nucifera*) syrup. Unique creamy texture and white colour are apparent in buffalo curd and the addition of palm trickle contributes to balancing the sourness or acidity of the product and contribute to improving its sensory acceptability when consuming as a dessert or snack. Consumption of *Meekiri* with boiled rice/ main meal is also reported in certain parts of Sri Lanka; however, it is less common

(body of the *Meekiri*) must not be in a gritty texture and should be able to obtain a clean cut with a spoon without cracks in the body. The texture of the body must be consistent without visible air pockets (Fig. 8A). Whey separation onto the surface, also known as syneresis, should not occur from the gel and may have a thin fat layer on top of the curd body. This is associated with the absence of a key processing step (e.g. homogenization) at small-scale rural production. Comparing the syneresis values between *Meekiri* and *Deekiri* has reported that *Meekiri* results in lower syneresis than *Deekiri* [33]. The pH of the optimal *Meekiri* must be 4.5–4.6. No major preservatives are recommended, where some producers add ascorbic acid up to 1 g/kg. The manufacture of *Meekiri* does not require any stabilizers, since buffalo milk contains a higher amount of fat, total solids compared to cow milk, where often a stabilizer is added when fermented gels are produced. Consumption of *Meekiri* is still mainly practised as a dessert [12] either with palm treacle: *kithul* (*Caryota urens*) or coconut (*Cocos nucifera*) syrup or table sugar (Fig. 8B), where many other culinary potentials are also available. The comparable product for *Meekiri* is *Dahi* in India. In the western world, a similar product for *Meekiri* is Greek-style yoghurt, a concentrated cow milk yoghurt, which has a similar mouthfeel and texture.

Microbiology of *Meekiri*

Production of *Meekiri* involves the use of starter culture bacteria, either sourced commercially or maintaining at the household level. Thus, a wide array of bacterial strains may occur and gives rise to various unidentified and unclassified properties [10, 34]. *Meekiri* contains lactic acid bacteria belonging to several genera. These bacteria can be incorporated into *Meekiri* either as starter cultures, can naturally stem from raw milk or introduced into milk during various steps in milk handling [34]. Traditionally, *Meekiri* from the previous fermentation is used as the inoculum to introduce starter cultures, i.e. back-slopping. Thus, microbial communities in *Meekiri* may highly vary among various production sites. From a recent study, we showed five different groups of LAB diversity at the species level from *Meekiri* samples collected from 22 local production sites across Sri Lanka [35]. Among those LAB isolated from *Meekiri* samples, we mainly identified *Limosilactobacillus fermentum*, *Latilactobacillus curvatus, Lactobacillus acidophilus* and *Lactiplantibacillus plantarum* with promising probiotic potentials. It has been found that *Meekiri* contains a combination of various lactic acid bacteria (i.e. *Lactobacillus delbrueckii* subsp. *lactis*, *L. planatarum, L. helviticus, L. delbrueckii* subsp. *bulgaricus* and *L. casei* subsp *casei*, *Streptococcus thermophiles* and *S. lactis*) in addition to *Saccharomyces cerevisiae, Micrococcus* spp., and *Bacillus* spp [36]. Kanthale is one of the popular regions in Sri Lanka for *Meekiri* production, and from this region, thirty-six *Lactobacillus* strains have been identified from spontaneously fermented traditional *Meekiri* in clay pots [37]. The microbiological composition of starter cultures used for the production of fermented buffalo milk has been investigated and identified as *Lactococcus lactis* ssp. *lactis*, *Lactococcus lactis* ssp. *cremoris*, *Streptococcus thermophilus*, *Lactobacillus delbrueckii* ssp. *bulgaricus*, *Lactobacillus acidophilus* and *Lactobacillus helveticus* [38]. Predominantly, the lactic acid bacteria available in raw milk contribute to the diversity of bacterial consortium in *Meekiri*. *Lactobacillus acidophilus* and *Lactobacillus delbrueckii* ssp. *bulgaricus* have been identified as the dominating species in raw buffalo milk, while *Streptococcus thermophilus*, *Lactococcus lactis* ssp. *lactis* and *Lactobacillus delbrueckii* ssp. *bulgaricus* were identified as the most abundant species in raw cow's milk [39]. The bacterial composition of buffalo milk and thus the *Meekiri* may be subject to vary with geographical areas and climatic conditions. Although to date, there is no published information available regarding the geographical variation of microbiota in *Meekiri,* as a consequence of variation associated with raw buffalo milk in Sri Lanka. From fermented buffalo milk in Pakistan, *Lactobacillus delbrueckii* subsp. *bulgaricus* and *Streptococcus thermophilus* have been identified as predominant lactic acid bacteria. Also, some contaminants, e.g. *Staphylococcus*, *Micrococcus* and *Saccharomyces* spp. were observed in fermented buffalo milk samples [40]. The raw milk microflora will further depend on buffalo's health status (e.g. mastitis conditions), diet and feeding practices, milking procedures, milk handling utensils, sanitation practices, and house flora. In raw buffalo milk, *Lactococcus* and *Streptococcus* dominated in the first 24 h and after storing it for 72 h, *Pseudomonas* and *Acinetobacter* genera have also been observed [41]. Therefore, the authors suggest that buffalo raw milk should immediately be chilled or processed to extend the shelf-life and must be monitored for the presence of *Paenibacillus*.

Evaluation of probiotic attributes of *Lactobacillus* spp. isolated from fermented milk from cow (*Deekiri*) and buffalo milk (*Meekiri*) samples collected from the Kandy district reported that they could grow at low pH (i.e. pH 3) and able to survive at 0.3% bile salt while showing antimicrobial activity against *E.coli* and *Pseudomonas aeruginosa* [42]. A research study investigating the shelf available *Meekiri* in Sri Lanka reported that the microbial count of *L. acidophilus* was higher than the minimum required level (10^7 CFU/g) up to 12 days of shelf-life and survived in low pH (1.5–4.24) with tolerance to bile salt [43]. This indicates that naturally occurring *Meekiri* tends to contain probiotic bacteria. According to FAO/WHO [44], probiotics are "live microorganisms which when administered in adequate amounts confer health benefits on the host". Probiotic bacteria contained in the buffalo milk most likely die during the heat treatment and probable probiotic bacteria might end in *Meekiri* though inoculum or house flora and might exert a probiotic effect on the host. Another study revealed that incorporation of *Bifidobacterium longum* into *Meekri* is possible and bifidobacteria showed a satisfactory survival of 10^6 CFU/g up to 3 days of storage in clay pots at 29 °C, while after 4 days of storage bifidobacteria counts were not acceptable [45]. However, the inclusion of probiotic bifidobacteria into *Meekiri* did not alter the organoleptic properties while improving consumer acceptability. *Meekiri* should be free from surface-grown mould and other external contaminants.

Quality defects

Consumer acceptance and satisfaction with *Meekiri* depends on its organoleptic quality attributes, and therefore, optimizing those properties is crucial to sustaining the *Meekiri* production in the market. Several quality defects, however, are visible in *Meekiri* as shown in Fig. 9.

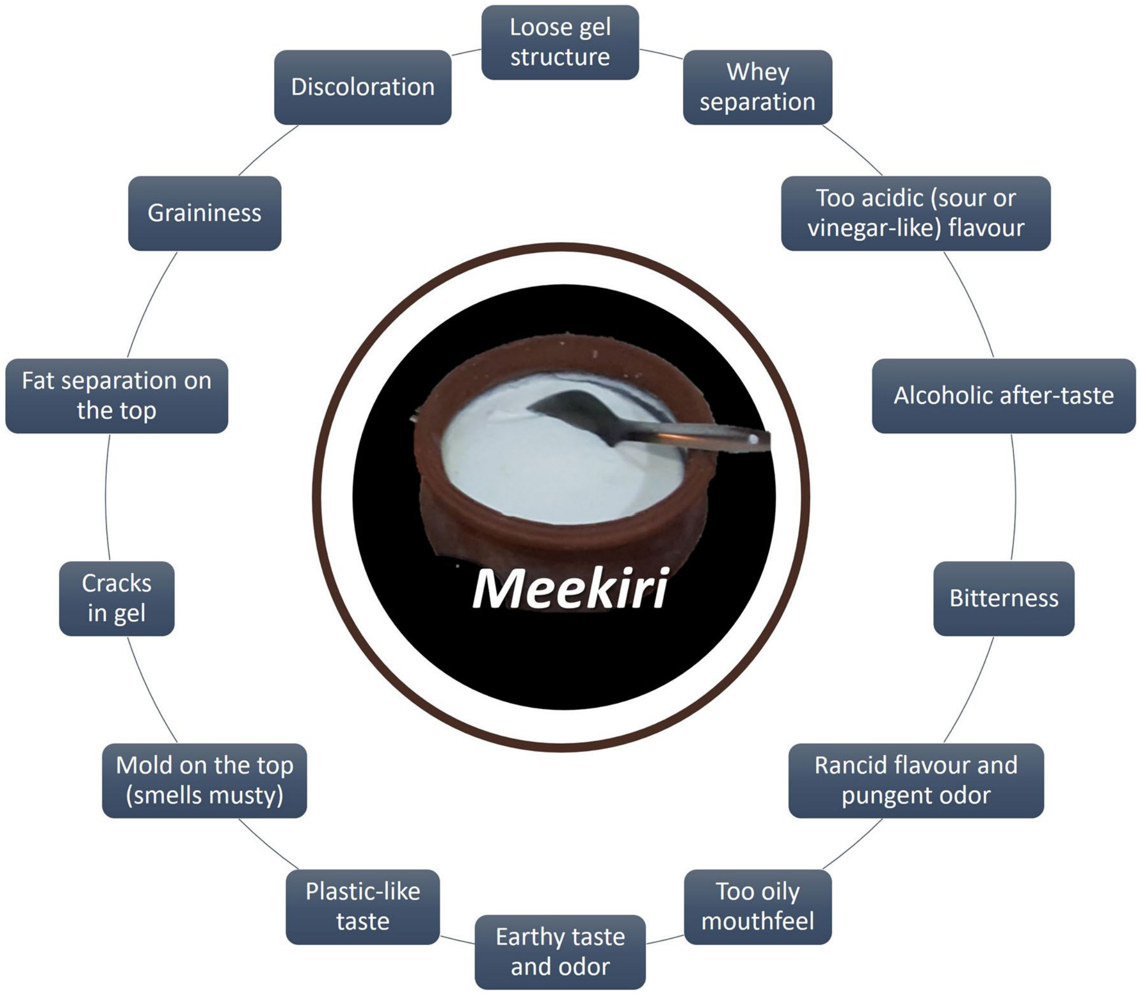


Fig. 9 Common quality defects in *Meekiri*. *Meekiri* is expected to have a strong solid-like gel structure with white colour creamy appearance. Loose gel structure and cracks, whey separation (syneresis), sour and unpleasant acidic flavour, alcoholic after taste, bitterness, rancid flavour and pungent odour, unpleasant oily mouthfeel, earthy taste and odour, paste-like taste, musty/mould smell, fat separation on the top, graininess, the discolouration can be considered as main quality defects in Meekiri. These quality defects can be categorized into two major domains: texture-related and flavour-related defects

Such quality defects can be mainly divided into two major domains, e.g. texture-related and flavour-related defects. *Meekiri* is expected to have a strong solid-like gel and often gel structure losing, cracks, syneresis are some of the common textural quality defects while sourness, too-oily mouthfeel, bitterness and taste associated with packaging are major flavour-related defects.

Product standards and adulterations

Sri Lanka Standards Institute (SLSI) [46] describes the *Meekiri* should have a minimum of 8.5% milk solids non-fat, 4.5 of maximum pH level and absence of *E. coli*. Buffalo milk, however, is often adulterated with cow milk, because cow milk is relatively high in availability on a year-round basis and lower farm gate price compared to buffalo milk [47]. This creates an ethical and legal requirement in detecting cow milk in buffalo milk or *Meekiri*. In Sri Lanka, two-thirds of the common market available *Meekiri* brands are adulterated with cow milk [48]. This mixing of both types of milk has an impact on the fat content, where it could lower the recommended level standards set by SLSI [46], of which the minimum level of fat percentage in *Meekiri* should not be lower than 7.5%. Apart from the compositional and organoleptic quality changes in *Meekiri*, the non-declared incorporation of cow milk into *Meekiri* will raise food safety concerns among the consumers with allergies or intolerance to cow milk [49].

Buffalo milk is rich in trace elements (e.g. iron, copper, zinc, manganese, selenium, iodine, chromium, molybdenum, cobalt, fluorine, nickel, silicon, arsenic and boron) and concentrations are varied with the stage of lactation, nutritional status and health condition of udder and animal, genetic factors, feeding and environmental factors. These elements can be accumulated in forage plants as a result of those been up taken from soil and water. When buffaloes graze on such sources, trace elements are transferred and reach the blood and then milk. A recent study conducted by the University of Peradeniya, Sri Lanka [50], found a variation in minerals among the buffalo milk samples ($n=78$) sourced from twelve locations in Sri Lanka. They reported buffalo milk collected from the Embilipitya area to contain a higher amount of Arsenic (As) and Lead (Pb), while samples collected from Weeravila and Ambalantota contained a lower amount of As and Pb, respectively. Higher calcium and potassium levels were reported from milk obtained from the Polonnaruwa area. Alarmingly, higher concentrations of As and Pb were found in *Meekiri* sourced from those areas. This is probably since *Meekiri* is mainly produced in clay pots, where the risk for contaminating the fermented milk with heavy metals is high from the clay. This is because clay absorbs toxic metal from its environment, holds inside the porous structure and mitigates into the *Meekiri*. However, results must be interpreted cautiously since the number of samples ($n=4$) analysed is very limited, raising concerns about reproducibility and representability. Yet, the study cast some light on these aspects, where no published data are available in this regard.

Safety aspects

In traditional *Meekiri* production, the milk base is first sieved to remove unwanted and extraneous materials present in the milk. Subsequent boiling (20–30 min) of milk or industrial pasteurization (72 °C, 15 s) destroys almost pathogenic microbes, many spoilage type microbes and enzymes that are deteriorating the milk proteins and fats. Fermenting buffalo milk into *Meekiri* has been suggested as an effective strategy to eliminate *Listeria monocytogenes*, where the growth of *Listeria* was not observed below the pH level of 5.5 [51]. This inactivation of *Listeria* is mainly due to low pH, increasing acidity and production of bacteriocins such as nisin. *Lactobacillus* strains found in *Meekiri* samples in Kanthale district, Sri Lanka, reported exhibiting strain-specific antimicrobial properties against several pathogenic bacteria, while demonstrating the highest antibacterial activity against *Listeria monocytogenus* [37]. Therefore, it can be argued that the natural microflora used in traditional *Meekiri* production in the Kanthale area in Sri Lanka have antibacterial activity, which could protect the curd from bacterial spoilage to enhance the shelf-life while enhancing food safety from food-borne bacterial diseases.

Nutrition and health benefits

Consumption of buffalo milk feels more satiety as compared to drinking the same amount of cow milk and thus provides numerous health benefits such as controlling the food intake. Therefore, it provides benefits for healthy bones and dental health. Buffalo milk is a good source of protein, for those who seek for high protein drinks to boost muscle mass compared to cow milk. Though buffalo milk is rich in fat, the level of cholesterol is lower and thus pauses comparatively less health risk compared to cow milk. Moreover, *Meekiri* contains a higher amount of vitamin A, which is important for normal vision. Buffalo milk contains a higher amount of minerals such as calcium and phosphate, while lower sodium content is compared to cow milk [52] and thus being a rich source of bioavailable essential minerals for consumption.

Consumption of *Meekiri* promotes health and the use of *Meekiri* in traditional medicines dated back to ancient periods in Sri Lankan history. *Meekiri* enhances lactose digestion, stimulates intestinal immunity and peristalsis [53]. In individuals suffering from lactase deficiency, lactose intake may cause intestinal discomfort, leading to a condition known as lactose intolerance. The reduction in the lactose concentration, as a consequence of fermentation, and the occurrence of a large number of viable bacteria containing β-galactosidase have allowed lactose intolerant individuals to consume fermented dairy products [53] such as *Meekiri*. Consumption of *Meekiri* can be used as a prevention and/or treatment for diarrhoea due to rotavirus infection and prolonged antibiotic use. Further, *Meekiri* has been considered favourable to overcome health conditions such as gastritis and constipation especially during critical periods of life such as pregnancy, lactation and times of ill health [54, 55]. Curd serves as a suitable delivery vehicle for probiotic bacteria which provide several health benefits through improved gut microbiota composition [56]. Moreover, since fermented milk products like curd were reported to prevent some cancers, reduce serum cholesterol and reduce hypertension [57], *Meekiri* may be used to treat such conditions.

Perception survey about *Meekiri*

To evaluate the general consumer perception about the *Meekiri*, we conducted an online survey using Mentimeter (Stockholm, Sweden). The survey was distributed among general consumers and a total of 123 responses were obtained. Respondents were asked to indicate their

Fig. 10 Wordcloud of descriptors indicated by survey participants regarding their first impression about traditional Sri Lankan fermented buffalo milk gel/*Meekiri*. Word sizes are proportional to the number of responses. A total of 123 responses were recorded from an online survey. Participants were treated without discriminating based on their demographic characteristics; however, all participants included in this survey were Sri Lankans

first impression of *Meekiri* in one word. Each responded had one opportunity to indicate their opinion and all responses were summarized in the word cloud in Fig. 10. The majority responded to *Meekiri* as "delicious".

Cost of production and economics of buffalo production

Buffalo plays a pivotal role in overall social development through supplying milk, meat, hides and draft power for agricultural operations [58]. Buffalo farming significantly contributes to the sustainability of mixed crop-livestock farming systems as well as to the farmers' income and food security in Sri Lanka [19]. According to the prevailing social, cultural and economic understandings among rural farmers, the dairy herd is considered as an easily convertible currency and a reliable living bank that not only provide daily subsistence but also the capital and ready cash at times of dire family needs to overcome the financial issues in the event of urgency [19, 20, 58]. Buffaloes are more efficient milk producers than indigenous cows [58]; out of two types of buffaloes (e.g. river-type and swamp-type), the river type has high lactation yields than swamp type and is thus suitable for milk production. Breeds like Murrah, Nili-Ravi, Mehsana, Jaffarabadi and Surti are examples of river-type buffalo breeds. Milk production costs are highly variable depending on the agro-ecological zone and the production system [20]. Revenues from milk include sales of milk and the value of milk consumed by the household [24], whereas the costs include concentrate feeds, housing, equipment, labour, medicine, services, insurance, fuel and transport, and animals.

The cost of production (CoP) of one litre of buffalo is varied depending on the locality and the production system. On average, the CoP of buffalo milk ranged from 40 to 55 Sri Lankan Rupees (LKR). The share of different cost components is varied depending on the system of production (Table 3). Cost for concentrates can be identified as the major cost component that varies from 41 to 47% (Table 3). The dairy industry in the peri-urban areas of Sri Lanka is a profitable industry with the opportunity cost of family labour. If the family labour is included as an opportunity cost, the farmer can produce a litre of milk for 43 LKR. If not included, a litre of milk can be produced for 28 LKR [25].

Future of *Meekiri*

Meekiri, being well-appreciated ethnic food in Sri Lankan food culture, will continue to be an integral food item across the ethnic and sociocultural groups. With the growing population, the demand for *Meekiri* is expanding. To cater for the growing market, modern dairy farming and dairy processing plants are emerging in Sri Lanka with the continuous adaptation of new technologies in

Table 3 The percentage share of different cost components associated with the cost of production of 1 L of buffalo milk in different buffalo production systems in Sri Lanka

Locality	Ratnapura (wet zone) [59]	Bingiriya, Pannala and Kuliyapitiya (coconut triangle) [20]	Seethawakapura (peri-urban) [25]
Labour cost	44%	15%	35.33%
Feeding cost	41.7%	47%	46.61%
Depreciation of initial investment	3.1%	NA	7.85%
Cost of veterinary services	3.2%	3%	10.2
Costs of death and losses	4.9%	NA	NA
Breeding and miscellaneous costs	3.0%	38%[a]	NA

NA not available

[a] Costs of housing, equipment, services, insurance, transport and animals

the processing of *Meekiri*. Commercial and large-scale production of *Meekiri* is becoming more prominent than cottage-level production, alarming the need for proper regulations in quality standards. The growing production capacities create the niche for adopting competitive, economically viable and sustainable strategies for long-term storage, preservation and marketing of *Meekiri* than ever before. To adopt the increased demand for buffalo milk for catering to the growing production of *Meekiri*, farmers tend to use improved buffalo breeds, artificial insemination programmes, improved feeding, intensive farming practices, improved housing conditions and overall management of dairy buffaloes.

Despite various barriers to consuming fresh milk due to allergies to bovine milk and lactose intolerance, fermented milk gels such as *Meekiri* could partly or completely overcome such limitations. Moreover, *Meekiri* is a rich source of calcium and it could fulfil the daily dietary requirement of calcium, which is ~ 1000 mg/day for pregnant women. In addition to fulfilling the nutritional needs, consumption of *Meekiri* can exert positive effects on the gut microbiota hence could be associated with overcoming or reducing the risk of various gastrointestinal disorders. Therefore, characterization and identification of microflora in traditional starter cultures in *Meekiri* and assessment of essential probiotic attributes and finally their applications in the preparation of probiotic incorporated functional fermented dairy products would be of utmost importance. Additionally, in vivo evaluation of desirable attributes of starter cultures originated from *Meekiri* for maintenance of normal microflora of the intestine and their antimicrobial properties which could be exerted due to competitive exclusion abilities or production of antimicrobial substances on pathogenic microbes must be thoroughly investigated.

Although value addition to *Meekiri* is not common in the regular market, value addition to consumer retail clay cups can be occasionally seen at high-end markets. Since its origin, *Meekiri* has been remained unchanged, without being subjected to be diversification as seen in regular cow milk yoghurt. However, scientific excellence in research on buffalo milk and coagulation into milk gel (curd) has undoubtedly gained more understanding about the quality of *Meekiri*. Further work must focus to improve the coagulation efficiency and properties of the final gel to cater for the growing demand with improved quality. For this purpose, the standard set by Sri Lankan Standard Institutes [46] must be reviewed and updated based on recent research findings, with the focus on preserving the value of authentic *Meekiri* and preventing possible adulterations of misleading products labelling.

Conclusions

Fermentation of buffalo milk into milk gel (curd), also known as *Meekiri*, is an indispensable dairy product in Sri Lankan food culture. *Meekiri* provides various health benefits, mainly due to its physicochemical attributes and ability to deliver probiotic microorganisms. Packaging materials and storage of *Meekiri* are important considerations. Up to date, extensive knowledge concerning the processing technology of *Meekiri* and its chemistry is available. There are, however, various knowledge gaps existing in the arena, highlighting the need for future research. Detailed quality characterization of buffalo milk produced in Sri Lanka is required, concerning various farm management practices and production strategies adopted at varying household levels. Future research should be aimed at breeding buffaloes for improved milk quality characteristics that are suitable for *Meekiri* production, identify the effects of farming systems, feeding practices and management on milk quality attributes. At present, buffalo milk is mainly used for *Meekiri* production and product diversification as well as innovation will play a key role in sustaining the buffalo farming industry. Moreover, consumption of *Meekiri* should be promoted in widespread culinary uses, as a functional food with numerous health-promoting benefits.

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Authors' contributions
HP conceptualized the idea, worked out the technical details and performed information collection, manuscript drafting and incorporating revisions. JKV, DR and CSR devised the conceptual framework, wrote and revised the paper with input from all authors. The author(s) read and approved the final manuscript.

Availability of data and materials
Not applicable.

Declarations

Competing interests
The authors declare that they have no competing interests.

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