Food Science and Technology 14(1): 1-10, 2026 http://www.hrpub.org
DOI: 10.13189/fst.2026.140101

Impact of Farm Hygiene Practices and Seasonal Variations on the Microbial Population of Raw Milk in Small-Scale Dairy Farms in the Istog Region of Kosovo

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Received September 25, 2025; Revised December 15, 2025; Accepted January 20, 2026

Cite This Paper in the Following Citation Styles

(a): *[1] Xhavit Bytyqi, Violeta Lajqi, Nazmi Hasanaj, Flutura C. Ajazi, Sami Makolli , "Impact of Farm Hygiene Practices and Seasonal Variations on the Microbial Population of Raw Milk in Small-Scale Dairy Farms in the Istog Region of Kosovo," Food Science and Technology, Vol. 14, No. 1, pp. 1 - 10, 2026. DOI: 10.13189/fst.2026.140101.*

(b): *Xhavit Bytyqi, Violeta Lajqi, Nazmi Hasanaj, Flutura C. Ajazi, Sami Makolli (2026). Impact of Farm Hygiene Practices and Seasonal Variations on the Microbial Population of Raw Milk in Small-Scale Dairy Farms in the Istog Region of Kosovo. Food Science and Technology, 14(1), 1 - 10. DOI: 10.13189/fst.2026.140101.*

Abstract This study evaluated the microbial quality of raw cow milk in relation to seasonal variation and on-farm hygiene practices across 102 small-scale dairy farms in the Istog region of Kosovo. In total, 1,574 bulk tank milk samples were collected over one year and analyzed using 3M™ Petrifilm™ Aerobic Count Plates to determine total aerobic colony counts (CFU/mL). Monthly mean counts ranged from 1.26×10^5 CFU/mL in December to 2.84×10^5 CFU/mL in January, with an overall annual mean of $1.99 \times 10^5 \pm 0.86 \times 10^5$ CFU/mL. The Kruskal–Wallis test showed significant differences among months ($p < 0.001$), while seasonal effects were not significant ($p = 0.586$), despite higher values in summer and autumn. Across farms, CFU/mL ranged from 2.0×10^3 to 1.0×10^6 ($p < 0.001$), indicating large inter-farm differences associated with udder hygiene, equipment sanitation, and milk cooling practices. Regular udder disinfection, thorough milking machine cleaning, and immediate milk cooling to ≤ 4°C are cost-effective priorities to improve milk safety and the economic sustainability of smallholder dairy farms.

Keywords Raw Milk, Bacteria, Hygiene Practices, Seasonal Variations, Farm Management

1. Introduction

At the European level, raw milk production remains a cornerstone of the agricultural sector, with the EU-27 producing approximately 160 million tonnes of cow's milk annually, accounting for more than 20% of global milk output. The largest contributors, Germany, France, the Netherlands, Poland, and Italy, collectively account for over 60% of this volume, reflecting the high level of structural development and intensive dairy management in these regions [1]. In contrast, milk production in the Western Balkans, including Kosovo, is predominantly characterized by smallholder-based systems, smaller average herd sizes, and considerable seasonal and managerial variability. In 2022, the number of dairy cows in Kosovo was 130,493 head, while total milk production amounted to 276,058 tons/liters [2]. The dairy sector is dominated by small farms, with many producing primarily for self-consumption, and the main challenges facing the industry include poor milk quality, low productivity, and low efficiency [3].

The quality of milk produced at the farm level depends on farm management practices, and hygienic milk production at the farm level is a key factor in protecting milk from microbial contamination and safeguarding consumers from milk-borne health risks [4]. Additionally, milk and products derived from dairy cows' milk can harbor various microorganisms and may be important sources of foodborne pathogens [5]. The microbiological safety of dairy products is therefore a public health priority, given the potential for food poisoning, zoonotic infections, and other milk-borne diseases [6]. As the consumption of unpasteurized dairy products grows, illnesses are expected to increase steadily; a doubling of the consumption of unpasteurized milk or cheese could lead to a 96% increase in outbreak-related diseases [7]. It was observed that 21 of 79 (26.6%) dairy producers who consumed raw milk had one or more pathogenic bacteria in their bulk tank milk [8].

At the farm level, microbial contamination of bulk milk occurs via 3 main sources: bacterial contamination from the external surface of the udder and teats, from the surface of the milking equipment, and mastitis organisms from within the udder [9]. Additional factors influencing microbial levels include the quality of milking hygiene, farm size, water softness, effective cleaning and disinfection routines, and thermal–humidity conditions on the farm [10]. Similarly, Murphy and Boor [11] indicated that elevated PI counts are most likely the results of dirty equipment, poor cooling, or residual soil on teat surfaces at the time of milking.

Storage and cooling conditions also have a strong influence on microbial behavior. However, deep cooling (2 ℃) and a combination of heating and refrigeration (≤4°C) significantly extended the SLQ and SLs of raw milk [12]. Sources of microbial contamination of milk must be minimized by adopting hygienic standards that can be easily evaluated.

The TBC is the most widely used measure of microbial quality of raw milk. It is measured in the United States using several approved methods, including the standard plate count (SPC), plate loop count (PLC), Petri film (3M) aerobic count, flow cytometry methodologies (e.g., Bactoscan, Foss Analytical), and others [13].

Recent studies (2020–2024) have expanded our understanding of how microbial populations in raw milk respond to both farm-level management and broader environmental factors. Raw milk quality is influenced not only by hygiene practices but also by seasonality, cooling capacity, and regional climatic conditions. It was reported that unsanitary milking equipment, dirty udders, and delayed cooling were among the most important contributors to elevated TBC in small-scale dairy systems [14]. Similarly, other research emphasized the continuing importance of hygienic indicators such as TBC and coliforms for risk assessment across the dairy supply chain and highlighted the need for more context-specific data from smallholder production systems [15].

Seasonal fluctuations in microbial load have been documented across diverse production environments. For instance, higher aerobic mesophilic plate counts were observed in summer (~6.25 $\log_{10}$ CFU/mL) compared with winter (~6.10 $\log_{10}$ CFU/mL) in Iranian milk collection centers [16]. Conversely, other findings documented higher bacterial loads in winter than in summer in certain agro-ecological zones, indicating that climatic effects may vary regionally depending on local management practices, ambient temperatures, animal housing conditions, and milk handling routines [17]. Such observations underscore the complex interplay between season, environmental parameters, and hygienic practices in shaping the microbial quality of raw milk.

Broader reviews have also identified substantial knowledge gaps. It has been noted that while large-scale dairies in many regions increasingly meet established microbiological standards, small-scale farms, particularly in transitional economies, remain underrepresented in the literature [18]. Importantly, existing studies often examine hygiene practices or seasonality separately, rather than integrating both factors to understand their combined influence on microbial outcomes. This gap is especially pronounced in the Western Balkans, where dairy production is dominated by smallholders, infrastructure varies widely between farms, and longitudinal data remain limited. Two critical gaps, therefore, remain in the current literature: a lack of longitudinal, full-year datasets that concurrently assess seasonal variation and hygiene practices in small-scale dairy systems and insufficient research from the Western Balkan context, where environmental pressures and farm heterogeneity may uniquely influence microbial patterns. Addressing these gaps is essential, as the interaction between season and hygiene may determine raw milk microbial load more strongly than either factor alone.

This study aims to evaluate the combined impact of farm-level hygiene practices and seasonal variation on the microbial load (CFU/mL) of raw milk over a full 12-month period in 102 small-scale dairy farms in the Istog region of Kosovo. By analysing 1,574 raw milk samples and linking microbial counts with documented hygiene practices and cooling infrastructure, this research provides a comprehensive, context-specific assessment of how seasonal and management-related factors jointly influence milk safety and quality in smallholder dairy production systems.

2. Material and Methods

The research includes 1574 milk samples from 102 small-scale dairy farms in the Istog region of Kosovo over one year. The farms included in the study breed 2 to 20 cows, mainly the Simmental and Holstein. The stables included in the survey breed cows in a tied system where the cows always stay tied with chains around their necks, in a "bed" or stand with a width of 80 - 100 cm and a length of 180 -

200 cm. The stable floor is made of concrete; the walls are made of bricks; and the roof is made of sheet metal. Approximately 90% of the stalls, as well as other conditions that existed in the investigated stables, are presented in Table 1.

2.1. Sampling of Milk

A total of 1,574 raw milk samples were analyzed during the study period, corresponding to 787 dairy farms. Farmers delivered milk from these farms to the local milk collection point, where microbiological analysis was performed twice a month for each contributing farm. Initially, the milk was subjected to the alcohol test, which is realized through the mixture of 2 ml of milk with 2 ml of 68% ethanol and gently swirling. Only the negative samples from the alcohol test were analyzed. After the negative result in the alcohol test, the milk was mixed well in the can, and 20 ml of milk was taken, placed in the "glass" for sampling, and immediately placed in the refrigerator at a temperature of 4 degrees Celsius. The seasonal distribution was as follows: Spring (210 farms/420 samples), Summer (187/374), Autumn (179/358), and Winter (211/422). These values represent the cumulative number of farmers delivering milk during each season and the resulting samples obtained through the set schedule of two samples per month. This approach ensured consistent sampling frequency and comparable representation across all seasons.

2.2. Method for Analyzing the Number of Bacteria (CFU/mL)

Microbial load was assessed using the 3M™ Petrifilm™ Aerobic Count Plates, which are validated for the enumeration of total aerobic mesophilic bacteria in raw milk, as per ISO 4833-1:2013 [19, 20]. 3 Petri Film Aerobic Count plates were taken from the refrigerator and placed on a flat surface. The upper film was lifted, and 1 mL of milk was aseptically transferred with a pipette and deposited at the center of the lower film, while maintaining the pipette in a perpendicular position relative to the plate. The top film was then released onto the sample, after which the inoculum was evenly distributed by applying gentle downward pressure at the center of the hydrated area using the spreader, carefully avoiding any lateral sliding. Following removal of the spreader, the plate was left undisturbed for one minute and subsequently placed in the incubator in a horizontal orientation, with the transparent side facing upward. The plates were incubated at 35 ℃ for 48 hours.

After the incubation period, the 3M™ Petrifilm™ Aerobic Count Plates were enumerated using a standard colony counter (3M™ Petrifilm™ Plate Reader), which automatically detected and counted colonies (visible as red dots), providing the total aerobic colony count. After enumeration, all used Petrifilm plates were properly disposed of according to laboratory safety procedures.

Given that the 1,574 milk samples analyzed for bacterial counts represented duplicate sampling per farm per month, the study reported the mean values of bacterial counts per farm per month (n = 787).

2.3. Statistical Analysis

Given the non-normal distribution of CFU/mL values (Shapiro–Wilk test, $p < 0.001$), non-parametric methods were employed. The Kruskal–Wallis H test was used to assess significant differences in microbial load across months and seasons. Bonferroni-corrected post hoc comparisons identified significant pairwise differences between months. Descriptive statistics (mean, median, standard deviation, range) summarized microbial data. All analyses were conducted using JASP v0.18.1.

The choice of non-parametric tests (Kruskal–Wallis instead of one-way ANOVA) was justified by the skewed distribution of microbial counts and presence of outliers, which violated the assumptions of homogeneity of variances and normality required for parametric tests.

Table 1. Farm management and hygienic conditions across the studied dairy farms

Stable/Milking Practice	Number of Farms (out of 102)	Percentage (%)
Release to pasture	24	23.52%
Artificial ventilation in the stable	7	6.80%
Disinfection of cow bedding	2	2.00%
Disinfection of the udder before milking	0	0.00%
Disinfection of the udder after milking	17	17.00%
Milking with a milking machine	94	92.00%
Disinfection of milking machines	29	28.00%
Possession of milk cooling equipment	13	12.70%

3. Results

3.1. About the Total Number of Aerobic Bacteria (CFU/mL) in the Months of the Year

The monthly microbial counts (CFU/mL) in raw milk from 102 farms in the Istog region are summarized in Table 2.

From the analysis of all valid samples (n = 787) for the average number of microorganisms (CFU/mL) in raw milk, values range from 2,000 CFU/mL (2.0×10^3) to 1,000,000 CFU/mL (1.0×10^6). The overall average across all months is approximately 199,747 CFU/mL, with considerable monthly fluctuation. Based on the monthly descriptive statistics, the highest average microbial count was recorded in January (283,949 CFU/mL), followed by June and April. In contrast, the lowest average was observed in December (125,813 CFU/mL), followed by March and August. The monthly sample sizes ranged from 52 (August) to 75 (June and December), indicating broad data representation. Standard deviations (SDs) and standard errors (SEs) were relatively high in most months, reflecting notable spread in CFU/mL values, with the highest SD in June (247,708) and the lowest SE in December (12,319). The Shapiro-Wilk normality test yields W = 0.791 and a p-value < 0.001, indicating a non-normal distribution. The Kruskal-Wallis test result is highly statistically significant (p-value = < 0.001), suggesting that the median CFU/mL values differ across at least some months of the year. The Post Hoc Bonferroni-adjusted test found that of 66 comparisons, 4 were statistically significant. The comparisons that yielded significant differences were April versus December (mean difference +123.5, p = 0.007), December versus January (mean difference -158.1, p < 0.001), December versus June (mean difference -126.9, p = 0.004), and January versus March (mean difference +134.9, p = 0.004). These results indicate that bacterial load in raw milk varies significantly between specific months of the year. Among the many factors that have influenced the results of the monthly average values of microorganisms in milk samples, some appear to have a greater seasonal impact (Figure 1).

The highest microbial counts were observed in Summer (222.65 CFU/mL) and Autumn (222.51 CFU/mL), followed by Spring (203.85 CFU/mL), while Winter (196.6 CFU/mL) had the lowest average. Although numerical differences are visible, particularly higher values and greater variability in Spring and Summer, suggesting that warmer seasons may be associated with higher bacterial counts in raw milk, the Kruskal–Wallis test indicated no statistically significant differences between seasons (H = 1.9338, p = 0.586). However, Winter shows lower and more consistent CFU/mL values, suggesting seasonally better milk hygiene.

3.2. About the Total Aerobic Bacteria (CFU/mL) in Milk from the Farmer

The descriptive analysis of CFU/mL in raw milk across farms revealed substantial variability, with values ranging from 2,000 CFU/mL at farm 80 in December as the lowest value, to 1,000,000 CFU/mL at farm 44 in June as the highest (Figure 2).

Due to the non-normal distribution of the data (confirmed by the Shapiro–Wilk test, p < 0.001), a non-parametric Kruskal–Wallis test was applied to compare microbial quality across farms. The test produced a statistic (H) of 172.312, with 98 degrees of freedom, and a p-value < 0.001, indicating statistically significant differences. Some farms have higher variance, suggesting inconsistent performance across the 12 observations. For example, Farm 44 has a very high variance (133839.66), indicating significant fluctuations in the variable measured. Farm 13 (Average: 287.46 CFU/mL) and Farm 41 (Average: 324.58 CFU/mL) appear to be high performers, while farms like Farm 58 (Average: 6.92) and Farm 66 (Average: 29.17) show much lower performance.

Table 2. Monthly variation in total aerobic bacterial counts (mean ± SD, $\times 10^5$ CFU/mL)

Month	n	Mean ± SD (CFU × 10^5/mL)	Median	Coefficient of Variation
January	68	2.84 ± 2.27	2.4	0.8
February	68	1.60 ± 1.57	1.2	0.98
March	64	1.49 ± 1.87	1.05	1.25
April	73	2.49 ± 2.05	2.1	0.82
May	73	1.87 ± 1.90	1.42	1.02
June	75	2.53 ± 2.48	2.1	0.98
July	60	1.73 ± 1.65	1.4	0.95
August	52	1.60 ± 1.46	1.28	0.92
September	57	1.88 ± 2.03	1.5	1.08
October	60	2.37 ± 2.28	2	0.96
November	62	2.07 ± 2.00	1.6	0.97
December	75	1.26 ± 1.07	1	0.85

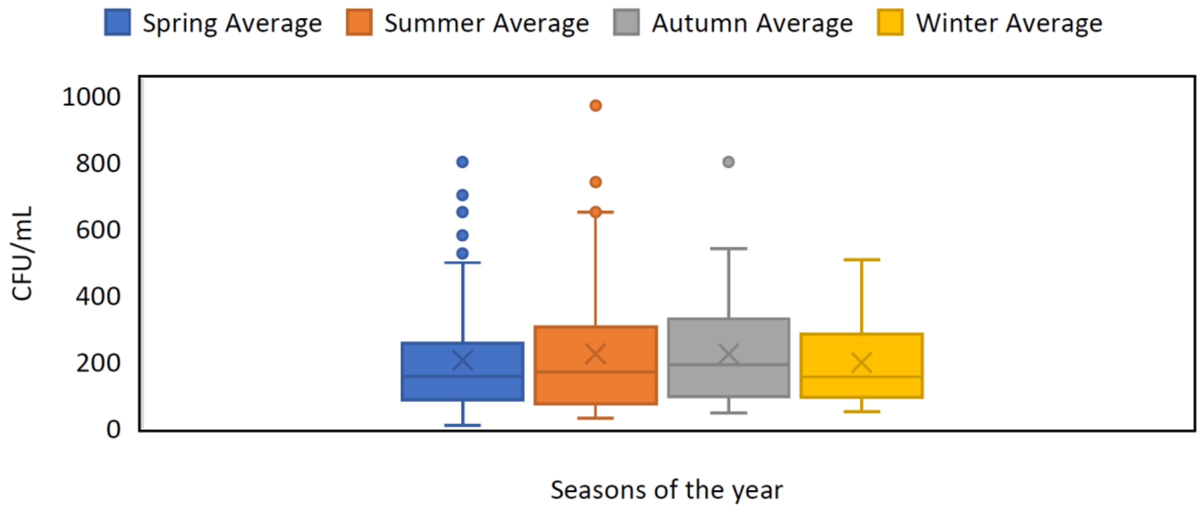

Figure 1. The seasonal fluctuation in the average number of microorganisms (CFU/mL)

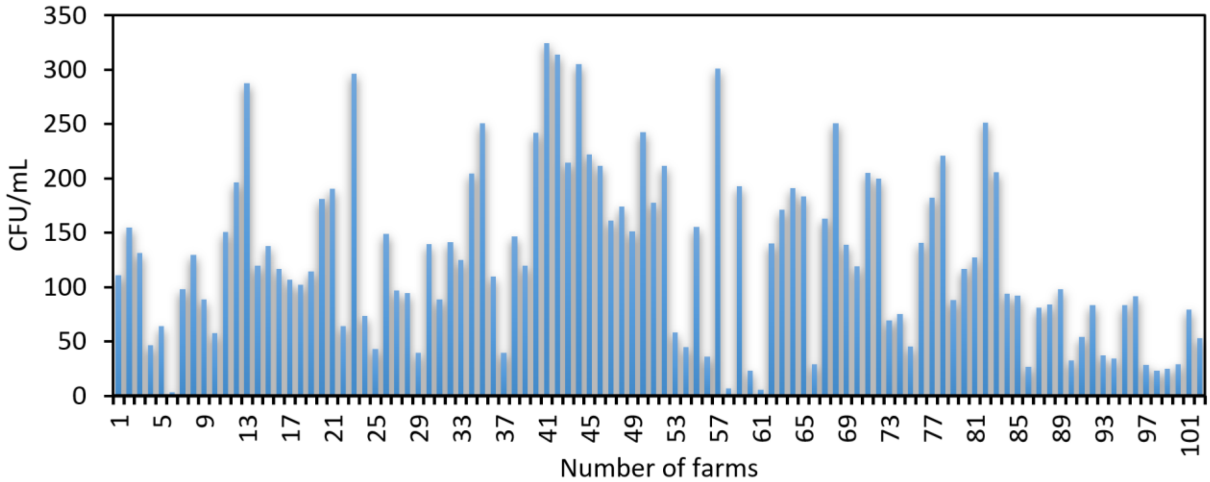

Figure 2. Monthly averages of the number of bacteria for the farms included in the study

4. Discussion

4.1. About the Total Number of Aerobic Bacteria (CFU/mL) in the Months and Seasons of the Year

The range of values (2 to 1000 CFU/mL) includes both very clean milk (almost sterile under practical conditions) and highly contaminated samples that may exceed local or EU safety limits for raw milk intended for consumption or processing. Comparatively, in the works of other authors, the corresponding values of the microbes studied were 6.24 ± 0.14. (1,740,000 CFU/mL) to 7,69 ± 0,13 (49,000,000CFU/mL) for TMAB [21]; The mean value of aerobic mesophilic bacteria was 6.78 log CFU mL^{-1}), (6,030,000CFU/mL) [22]; The average aerobic mesophilic bacterial count was 9.0 log10 CFU/mL, (1,000,000,000 CFU/mL) [23], and 8.2 ± 1.71 log CFU/mL (158,000,000 CFU/mL) [24] or that bacteria heavily contaminated fresh raw milks collected from farms with a mean total plate count (TPC) of 12×10^6 CFU/ mL^{-1} (12,000,000 CFU/mL) [25].

The study confirms that statistically significant differences in CFU/mL exist between certain months, and this fact supports the interpretation that observed differences are not random but reflect systematic and potentially controllable factors at the farm level, reflecting underlying seasonal or operational influences. January consistently shows higher microbial contamination, whereas December, March, and July demonstrate relatively improved microbial quality. Similar monthly variability has been described elsewhere, such as differences in raw milk microbiota across January–June, July–August, and September–December [26], and that both month and year are factors that interfere with TBC [27].

When it comes to the influence of seasons on CFU/mL in milk, it turns out that seasons also have had an impact on the microbiological quality of raw milk, with higher contamination during Summer and Autumn and the lowest microbial counts in Winter, although the differences are not statistically significant. Thus, Winter is the most consistent season, suggesting that cold temperatures naturally inhibit bacterial and higher contamination during Summer and Autumn. The observed seasonal variation in microbial counts is likely driven by the combined influence of thermal conditions, humidity levels, and farm-level management practices. Elevated temperatures during summer can shorten bacterial doubling times, increasing the intrinsic growth potential of psychrotrophic and mesophilic microorganisms in raw milk. In the absence of rapid cooling below 4 ℃—common among smallholder farms in the region—this effect becomes more pronounced. Conversely, winter conditions reduce microbial growth rates but introduce other risks such as increased internal stable humidity, inadequate bedding hygiene, and limited mechanical ventilation, which facilitate the contamination of teat surfaces. Heterogeneity among farms in udder hygiene routines, frequency of equipment sanitation, water temperature used for cleaning, and the availability of cooling tanks further explains inter-farm differences. Such management disparities are consistent with previous research demonstrating that hygienic milking procedures can reduce bacterial load by up to 1–2 log units in raw milk.

When reviewing the results achieved by other authors, variations in the number of microorganisms throughout different seasons are noted. It is noticed that the number of microorganisms in fresh milk is also affected by other environmental factors, such as temperature, humidity, and season of the year [28]. Seasonal factors contribute to approximately 10–12% of variation in milk microbiota composition, with spring and summer samples often displaying higher alpha-diversity [29]. Heat stress triggered by climatic conditions can further elevate microbial counts and increase cows' susceptibility to pathogens [30,31].

The present study demonstrated statistically significant monthly differences in microbial load ($p < 0.001$), with the highest mean bacterial counts recorded in January (2.84×10^5 CFU/mL) and the lowest in December (1.26×10^5 CFU/mL). Although seasonal differences were not statistically significant, a clear tendency toward higher microbial loads during summer and autumn and lower values during winter was evident. Comparable patterns have been documented in previous work from similar climatic settings. For example, an investigation of seven dairy farms across diverse geographic regions of Kosovo reported mean CFU values (194,048 mL^{-1}) exceeding national regulatory thresholds, with the lowest bacterial counts occurring in summer; however, seasonal differences were statistically non-significant [32].

These findings align with studies conducted in other continental and Mediterranean regions, where elevated ambient temperatures and increased humidity during the warm season facilitate bacterial proliferation in raw milk. In the Banat region of Romania, 4.2% (3/72) of processed reservoir milk samples exceeded the European Union threshold of 6.18 $\log_{10}$ CFU/mL for total aerobic mesophilic bacteria, indicating similar temperature-driven microbiological challenges [33]. Likewise, an assessment of raw milk collected from five dairy farms in Hungary between February and November showed that the highest somatic cell and coliform counts occurred during spring, while the lowest total bacterial counts were observed during winter; the interaction between production year and season was significant for all milk quality traits ($p < 0.05$) [34]. Comparable observations have also been made outside Europe. In Iranian Holstein herds, total bacterial counts increased by approximately 13.7% as environmental temperatures rose from 6 ℃ to 31 ℃ [35], while both somatic cell counts (SCC) and total bacterial counts (TBC) were lowest during the winter months [36]. Taken together, these studies corroborate the present findings and highlight the consistent influence of climatic and seasonal conditions on the microbial quality of raw milk across regions with similar continental-Mediterranean environmental characteristics.

Evidence of seasonal influence on CFU/mL can also be demonstrated if we focus on the fluctuations in the number of farmers who delivered milk to the collection point. A clear decrease in their number is observed, starting in June when their number was highest (n=75), decreasing in July (n=60), and reaching the lowest number in August (n=52). Their number begins to "recover" from September (n=57), October (60), and November (n=62), and returns to the number of farmers in both June and December (n=75). The decrease in the number of farmers to 20% in August can be related to the impact of high temperatures and thermal stress that starts in June and reaches their peak in August. The increase in seasonal temperatures and the lack of cooling devices for milk have increased the values of CFU/mL in milk. As a result, farmers abstained from delivering milk due to dissatisfaction with the lower classification of their milk with more bacteria, which consequently resulted in a lower payment for 1 liter of milk. This suggests that in August, only farmers who had better hygiene management and therefore had continuity throughout the year were delivering milk, being less influenced by external seasonal factors, including the impact of high temperatures. The decline in the number of farmers and their "failure" to maintain the lowest level of CFU/mL in milk in the period June-December is reflected in Figure 3, which shows the fluctuation of the number of farmers around the average number of farmers per month/year, which is n=65.

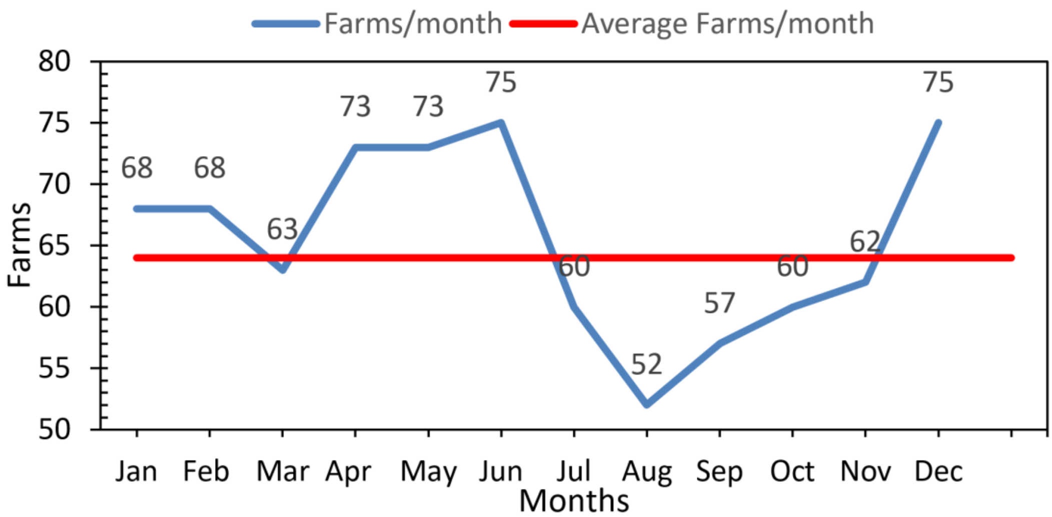

Figure 3. The number of farms per month, based on the annual average (n=65) of farms

4.2. About the CFU/mL among the Farms

The differences in CFU/mL among the 102 farms are statistically significant, indicating that the observed variability is not the result of random fluctuation but instead reflects systematic differences in farm-level hygiene management practices, equipment sanitation, cooling effectiveness, or milking routines. Some farms maintain excellent microbiological quality reflected by very low CFU/ mL values, while others repeatedly report extremely high microbial loads. The fact of the influence of technological factors on the different CFU/mL results in the farms studied can also be supported by the CFU/mL results based on months. Although results with lower CFU/mL values are obtained in the warmer seasons and vice versa, however, when CFU/mL values are considered separately, it becomes evident that the highest CFU/mL values appear in January (283,949 CFU/mL), which is currently part of the winter season, or the lowest values in July (173.19 CFU/mL), which is part of the summer season.

Considering that the farms studied offer almost the same general breeding conditions (closed system, milking on the bed, no cooling of the milk), it seems that the differences in the results for the number of microorganisms in milk are due to differences in farm management practices on the different farms included in the study. During the visits to the researched stables, we have noticed great differences in the treatment of cow bedding hygiene and cow udder hygiene before milking. These different levels of hygiene in the bedding and cowshed are among the causes of the results obtained in our research, and we support this with the work of other authors. These management differences are consistent with previous research demonstrating that bedding characteristics and cow hygiene strongly influence mesophilic and thermophilic spore levels in bedding and raw milk [37]. Similarly, intensive dairy farms adopting full milking routines in Lombardy produced milk with lower SPC and reduced bacterial counts [38], while improvements in management reduced microbial levels in chilling centers from log 7.08–6.88 to log 5.91–5.85 CFU/mL [39].

During field observations, nearly all interviewed farmers reported washing the udder before milking, but none used chemical disinfectants; 37% used lukewarm water, while 63% relied solely on cold water. Evidence from teat-cleaning interventions demonstrates that simple hygiene improvements can reduce mesophilic and thermophilic spores by 37% and 40%, respectively [40].

The impact of milking methods seems to be part of the influence on the results obtained with several microorganisms. Also, most farmers used mobile milking machines; 72% of them stated that they cleaned the machine, the pipe system, and the teat cups only with hot water, without using a disinfectant solution. A study from another author states that technological and hygienic factors during milking influence microbial counts in milk. Thus, machine-milked samples averaged 3.5×10^5 CFU/mL, while conventional milking yielded 2.9×10^6 CFU/mL. An Independent T-test confirmed a significant difference between the methods ($p < 0.05$), with poor hygiene contributing to higher SPC in machine-milked samples [41].

The elevated microbial loads identified in several farms—even during periods characterized by lower ambient temperatures—indicate that deficiencies in hygienic practices exert a stronger influence on raw milk microbiological quality than environmental conditions alone. Poor udder hygiene, inconsistent sanitation of milking equipment, and the absence of appropriate milk cooling and storage protocols contribute substantially to bacterial contamination, more so than seasonal temperature fluctuations. These findings underscore that substantial improvements in milk hygiene can be achieved through enhanced behavioral and procedural practices at the farm level, even in the absence of major infrastructure investments.

This study also provides essential baseline evidence for Kosovo's small-scale dairy sector, which structurally resembles those of other Western Balkan countries, characterized by fragmented production systems, reliance on manual or semi-mechanized milking, and limited access to modern cooling technologies. The results are consistent with observations reported in Albania, where the dairy sector continues to face systemic challenges, including outdated practices, insufficient infrastructure, and inconsistent milk quality standards; notably, except for large dairy cow farms, most lack adequate manure management facilities [42]. These results also reflect broader regional challenges. Similar issues have been reported in Serbia, Montenegro, and North Macedonia, where fragmented smallholder systems, outdated practices, and inadequate hygiene infrastructure remain widespread [43–45]. Improving farmer training, strengthening extension services, and standardizing hygiene practices could generate significant regional improvements in milk quality.

Overall, the observed disparities among farms indicate substantial potential for improvement. By adopting best practices demonstrated by higher-performing farms, underperforming producers can significantly reduce microbial contamination. Establishing standardized production and hygiene protocols across all 102 farms would help reduce CFU/mL levels, enhance milk safety, and support the long-term sustainability of the smallholder dairy sector.

5. Conclusions

This study confirms that raw milk is highly susceptible to microbial contamination and that contamination levels vary throughout the year, largely driven by on-farm practices rather than environmental conditions alone. Although seasonal differences were not statistically significant, a consistent numerical pattern was observed in which bacterial loads were highest in summer and lowest in winter, indicating that warmer temperatures combined with insufficient milk cooling amplify microbial growth.

Marked differences in CFU/mL among farms with similar structural conditions highlight the decisive influence of hygiene management. Farms that maintained proper udder hygiene, regularly cleaned milking equipment, and handled milk appropriately consistently achieved lower bacterial counts, whereas the absence of cooling systems and irregular disinfection routines remained major constraints to microbial quality.

Improving milk safety, therefore, requires targeted interventions, including farmer training, adoption of cost-effective cooling technologies, and implementation of standardized hygiene protocols. For farmers, simple measures such as enhanced udder hygiene, routine equipment sanitation, and rapid cooling to ≤4 °C can substantially reduce contamination. For processors, understanding seasonal and farm-level variability supports better collection planning, focused farmer support programs, and quality-based payment systems.

Strengthening hygiene and handling practices across the dairy value chain is essential for improving milk safety, enhancing product quality, and increasing the economic sustainability of smallholder dairy production in the region.

Conflict of Interest

Nothing to declare.

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