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Occurrence of Mineral Oil Hydrocarbons in Feed and Milk: Implications for Sustainable Dairy Production

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Abstract

Mineral oil hydrocarbons (MOH) are increasingly reported in agri-food systems, but their presence in dairy production is not yet fully characterized. This study investigated the occurrence of mineral oil saturated hydrocarbons (MOSH) and mineral oil aromatic hydrocarbons (MOAH) in feed and milk collected from three dairy farms with different production conditions, with the aim of supporting a system-wide interpretation of contaminant presence. Samples were analyzed using confirmed chromatographic methods, and the results were descriptively evaluated to express variability both within and between farms. Both feed and milk samples showed heterogeneous contamination patterns, highlighting the influence of environmental exposure, technological activities and biological variations, rather than a direct linear transfer. To help the interpretation, a conceptual framework linking environment, feed, animals and milk was proposed. From a sustainability point of view, the results highlight the importance of preventive monitoring and farm-level management strategies to reduce contaminant pressure in dairy production. Overall, the study furnishes empirical evidence that contributes to a broader understanding of contaminant occurrence and supports integrated approaches for food safety and sustainable dairy production.

Keywords: mineral oil hydrocarbons; dairy products; feed contamination; sustainability

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Academic Editor: Dario Donno

Received: 27 February 2026
Revised: 12 March 2026
Accepted: 13 March 2026
Published: 16 March 2026

1. Introduction

The concept of sustainability in the dairy industry increasingly focuses on the interdependence between food chain integrity and the quality of the finished products [1]. In a highly globalized food industry, sustainable production cannot be separated from food safety requirements [2]. Any contamination that endangers consumer health compromises the basic social and economic pillars of sustainability [3]. Dairy quality is a direct outcome of a safe food chain, which implies animal production carried out in a controlled environment and protected from anthropogenic pollutants [4,5].

Dairy production, in particular, is vulnerable and highly sensitive to pressures from environmental pollution. The strong dependence of dairy production on feed resources largely contributes to this vulnerability. Because feed can be a primary source of animal exposure to contamination, a direct relationship may exist between the consumption of contaminated feed and the presence of residues in milk. The complex interaction of environmental, technological, and biological factors also influences the safety of dairy products. Among the factors, these include the influences of geographical location or background pollution (environmental factors), the degree of mechanization of farm operations and storage management (technological factors) or the capacity of milk to retain lipophilic compounds due to its high fat content (biological factors) [6].

Over the past two decades, the conceptual framework regarding environmental contamination in the dairy production chain has broadened considerably [7]. Earlier studies mainly focused on “classical” contaminants, such as heavy metals, pesticide residues and mycotoxins present in soil, water and feed resources [8,9]. These contaminants were primarily associated with agricultural practices and environmental pollution, which could affect forage crops and subsequently be transferred to animals and dairy products [9]. However, the intensification of agricultural production and the development of industrial food processing technologies have introduced additional contamination pathways. In particular, the mechanization of agricultural operations and the use of petroleum products in agricultural machinery and processing equipment have increased attention toward contaminants such as mineral oil hydrocarbons (MOH) [10,11]. Recent studies have highlighted that pollution transfer is not only a local phenomenon but often follows complex spatial dynamics. It is important to understand contamination pathways within production systems and their implication for environmental sustainability and public health. For example, Hu et al. [12] demonstrated that pollution transfer processes may form structured networks influenced by economic and technological proximity, which can redistribute environmental risk and generate environmental health inequalities. Overall, current research recognizes that contamination of dairy products results from a combination of environmental, agricultural and technological factors along the entire production chain, highlighting the need for integrated monitoring strategies [13].

Mineral oil hydrocarbons (MOH) represent a relatively recent and emerging challenge that is not yet fully understood and addressed. The importance of this issue lies, particularly, in the link it establishes between environmental pollution and consumer health risks through bioaccumulation within the food chain [10]. Mineral oil hydrocarbons (MOH) represent a class of contaminants of petrogenic origin that affect the safety of animal production through their bioaccumulation capacity [14,15]. They are divided into two fractions: MOSH (Mineral Oil Saturated Hydrocarbons), known for their tendency to accumulate in adipose tissues and organs, and MOAH (Mineral Oil Aromatic Hydrocarbons), which are suspected to pose genotoxic and carcinogenic risks [10,16].

Mineral oils are used in a wide range of applications, including food-grade lubricants, processing aids, adhesives, coating agents and glazing agents [17,18]. Unlike conventional pollutants, MOH are ubiquitous in modern agriculture due to the extensive use of petroleum-derived products in machinery, logistics and packaging [6]. Throughout the dairy production chain, the entry pathway of mineral oils hydrocarbons includes multiple points of contamination or migration. The development of dairy production systems, although focused on efficiency, has inadvertently increased the risk of introducing these contaminants along the food chain and within the ruminant production cycle [10]. Atmospheric deposition resulting from road traffic, air transport and industrial activities that may contaminate forage crops can act as sources of background environmental contamination with MOSH and MOAH [19–22].

Particular attention should be paid to potential technological sources of contamination. During fodder harvesting and processing, inadequate production practices, such as the use of poorly maintained mechanized agricultural machinery, pose risks through lubricant leakage, hydraulic fluid release, emissions, suspended particles, or exhaust gases [18,23,24]. Certain active substances in plant protection products used in crop management and the storage of plant materials may contain MOSH and MOAH [15]. A representative example is paraffin oil, which is used as an adhesive or active substance in plant protection products [18]. Mineral oil products can also come into accidental or unintended contact with finished products through migration from various packaging materials during transport or storage. Mineral oil hydrocarbons present in food packaging and contact materials can enter food through direct contact or via the gas phase (evaporation, transport and recondensation). Recycled paper or cardboard packaging may contain mineral oil-based inks, jute bags, used technical oils, or equipment components in processing units; all can act as contamination sources for dairy products [21,25]. Some of these food contact materials may exhibit higher levels of MOH due to deliberate treatment or coating with mineral oil products [18].

The intake of MOH through cattle feed resulting from environmental pollution or technological contamination is increasingly being studied [6]; although this route of entry is plausible, it requires further supporting evidence from more studies [18]. In the ruminant organism, monitoring the fate of contaminants involves complex toxicokinetic processes. Once ingested, contaminants can be absorbed through the intestinal epithelium [10,26], metabolized, distributed via the bloodstream, and afterwards retained in tissues or eliminated in various forms [27]. These processes can influence the presence of contaminants in milk, given that lactation represents a major route for the excretion of lipophilic substances. Furthermore, milk fat acts as a reservoir for contaminants mobilized from the bloodstream or adipose stores of the cow [6]. The presence of contaminants in milk, however, does not necessarily reflect a direct or linear transfer from feed but rather the cumulative result of exposure shaped by biological and environmental factors.

Previous research has confirmed the presence of mineral oil hydrocarbons in food products [21,28–32] mainly characterizing them as isolated contamination events. More recent studies have documented the presence of MOH across different segments of the food chain and increasingly focus on broader system-level interactions that influence contaminant occurrence [24,33]. In this context, we understand that the long-term sustainability of dairy production systems relies on a more integrated analysis of the interconnections between the final product and the management of the production environment [1].

The objective of this paper is to investigate the occurrence of contaminants across the dairy production chain by analyzing their presence in feed and milk samples collected under real farm conditions. Using field data obtained from three dairy farms, the study examines contamination patterns within production systems and explores whether an association may exist between feed contamination and the presence of contaminants in milk. Specifically, feed may act as a potential contamination vector and milk as a final exposure compartment in which contaminant occurrence may be observed. To support the interpretation of the experimental results, a conceptual framework was developed to describe the possible relationships between environmental exposure, feed contamination, and contaminant occurrence in milk. This framework, illustrated in Figure 1, is used as an interpretative tool for discussing the field data analyzed in this study from a sustainability-oriented perspective. Although part of the analytical data regarding MOSH and MOAH occurrence in feed and milk has been previously reported in the literature, the objective of the present study is not limited to the presentation of analytical results. Instead, this work aims to provide an integrated interpretation of contamination patterns within dairy production systems by combining field observations with previously reported analytical data. In this regard, the study explores potential contamination pathways linking feed and milk and discusses their implications for monitoring and preventive management strategies in sustainable dairy production.

The proposed framework presents the main elements that may be involved in contaminant occurrence within dairy production systems and provides a structure for interpreting the field data analyzed in this study. It includes four operational compartments: environment, feed, animal, and milk. The environment, encompassing both natural and anthropogenic activities, is considered a potential source of contaminants. Feed represents the central compartment and the main exposure vector for animals. The animal organism functions as an intermediate biological compartment, the transformation system that acts as an exposure modulator that influences the appearance of contaminants in milk. Milk may reflect cumulative exposure, serving as the final exposure compartment for consumers. It should be noted that the proposed model does not refer to a direct or linear transfer of contaminants, but rather highlights their conditional occurrence, subject to environmental, technological and biological factors. The conceptual representation of relevant relationships is illustrated in Figure 1, which are further discussed in Section 4 in relation to the experimental results obtained in this study.

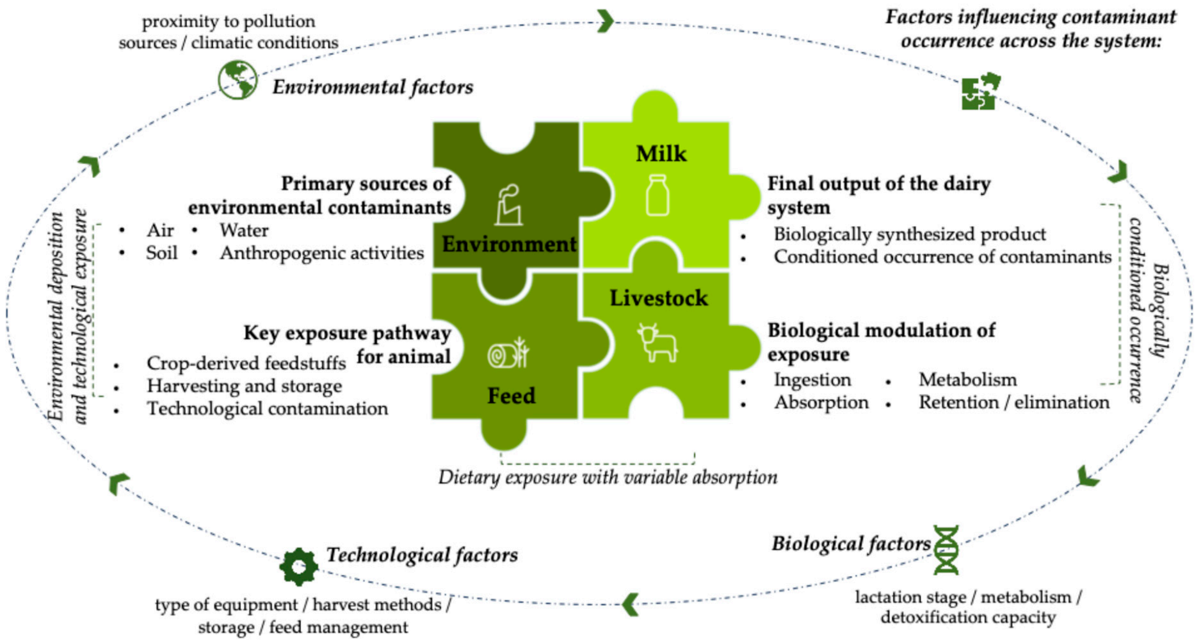


Figure 1. Schematic representation of contaminant occurrence across the dairy production chain and the relationships between environment, feed, animal and milk compartments.

2. Materials and Methods

This study represents a mixed conceptual (theoretical) and experimental (applicative) investigation aimed at describing and evaluating the relationship between feed contamination and the presence of contaminants in milk, based on analytical data obtained under real conditions that may clarify the possibility of transfer along the food chain. In this context, the methods describe how the experimental data were obtained and integrated to support the framework, thereby ensuring the methodological transparency of the study. Detailed descriptions of the sampling procedures, analytical methods, and contamination levels are reported elsewhere [6,33].

2.1. Farm Description

Three dairy farms located in the North-Eastern region of Romania were included in this study based on a preliminary evaluation of potential contamination risk. The farms operate under different environmental and technological contexts, with distinct feed management practices and heterogeneous contamination exposure scenarios. The selection process included structured interviews with farm managers, direct field observations, and an assessment questionnaire designed to identify possible environmental and technological sources of contamination within each production unit. The questionnaire addressed several aspects relevant to contaminant exposure, including the composition of the feed base, traceability of agricultural practices, fertilization and phytosanitary treatments applied to crops, the use of machinery and technical oils, feed processing and storage practices, and the proximity of farms to potential pollution sources such as urban areas, industrial activities, or transport infrastructure. Farm 1 represents a semi-intensive production system located in a mountainous agricultural area characterized by limited mechanization and relatively low exposure to external pollution sources. Farm 2 operates in a rural agricultural zone with moderate mechanization and mixed crop-livestock activities. Farm 3 is situated closer to an urban and industrial environment, where intensive machinery use, transport infrastructure, and nearby urban activities may increase the potential for environmental contamination. Additional contextual information regarding local environmental characteristics, including distance from urban centers, traffic intensity, and surrounding agricultural activities, was recorded to support the interpretation of potential contamination pathways within the studied dairy production systems. These farms have been previously characterized for feed and milk contamination with mineral oil hydrocarbons (MOSH and MOAH), providing a heterogeneous exposure setting and detailed background information on exposure [6,24,33].

2.2. Feed and Milk Sampling

Feed samples from the daily rations provided to lactating cows were collected from the feed base of the three selected dairy farms during the feed production and storage campaign conducted in 2021–2022. Different types of feed materials were included in the sampling procedure, consisting mainly of feed derived from crops potentially exposed to environmental and technological contamination; this includes green fodder, dry fodder, silage, and concentrated feed components used in the daily ration of dairy cows. Sampling was performed at different stages of the feed management chain, including the crop field, harvesting operations, transport stages, and storage facilities, in order to capture potential contamination pathways associated with both environmental exposure and technological practices.

A total of 15 feed samples were obtained for laboratory analysis, distributed as follows: two samples from Farm 1, five samples from Farm 2, and eight samples from Farm 3. The sampling design considered the size of the feed production areas and the participation of each feed component in the farm ration. In addition, milk samples were collected from each farm to explore the possible occurrence of mineral oil hydrocarbons in the final animal-derived product. Milk samples were obtained from cows that consumed the sampled feed during the same production period. A total of eight milk samples were analyzed, including four samples from Farm 1, two samples from Farm 2, and two samples from Farm 3. The number of milk samples reflects the exploratory character of the study and the availability of samples during the field sampling campaign under real farm conditions.

Samples were collected using standard sampling procedures, packaged in clean containers, labeled, and transported to the laboratory for further analytical processing. Additional methodological details regarding the sampling strategy and feed characterization have been reported in previous studies describing the contamination assessment protocol for their farms [6,33].

2.3. Analytical Determination of MOSH and MOAH

The analytical determination of MOSH and MOAH in feed and milk samples was performed using the same validated LC-GC-FID methodology previously described by Matei et al. [6], Matei et al. [33], Bauwens et al. [34], Moret et al. [35]. The analyses were carried out in the Food Chemistry Laboratory of the Department of Agricultural, Food, Environmental and Animal Sciences, University of Udine (Italy). The analytical system consisted of an LC-GC 9000 interface (Brechbühler AG, Zurich, Switzerland) coupled to a Phoenix 9000 HPLC and a Trace 1310 gas chromatograph equipped with a flame ionization detector (FID) (Thermo Fisher Scientific, Waltham, MA, USA), configured for the simultaneous determination of MOSH and MOAH fractions. No modifications were applied in the present study. Quality control procedures were performed as outlined in the referenced studies. The method complied with the analytical performance criteria set out in the Joint Research Centre (JRC) Guide [14].

From a regulatory perspective, European authorities currently provide mainly guidelines and monitoring recommendations regarding the presence of mineral oil hydrocarbons (MOH) in food and feed matrices. Within the European regulatory framework, maximum levels for several contaminants in food are established under Commission Regulation (EU) 2023/915 on food contaminants [36], while undesirable substances in animal feed are regulated by Directive 2002/32/EC [37]. However, specific legally binding limits for mineral oil hydrocarbons (MOSH and MOAH) in milk and feed have not yet been established at the EU level. Consequently, monitoring of these contaminants is mainly guided by EFSA risk assessments [10] and Commission Recommendation (EU) 2017/84 [38], which encourages the monitoring of MOH in food products. In 2022, the European Standing Committee on Plants, Animals, Food and Feed recommended the withdrawal from the market of food products exceeding the quantification limits proposed by JRC, depending on fat content (0.5 mg/kg for foods with a <4% fat; 1.0 mg/kg for foods with $\geq$4% and $\leq$50% fat) [39,40]. More recently, Moret et al. [41] explained that the European Commission circulated a draft regulation aimed at integrating MOAH limits into the Commission Regulation (EU) 2023/915 [36], with discussions ongoing for specific food matrices. According to revision of the SANTE PLAN 2023/2345 [42], indicative limits have been proposed for certain products in the next few years.

2.4. Use of Field Data for System-Level Interpretation

The available experimental data were analyzed descriptively to characterize the occurrence and variability of MOSH and MOAH in feed and milk samples across the studied dairy production systems. The analysis focused on identifying contamination patterns within and between farms without assuming direct transfer relationships between the investigated compartments. The proposed conceptual framework was subsequently used as an interpretative structure to discuss how the observed patterns may relate to environmental exposure, technological practices, and biological modulation within dairy production systems. The following section presents the experimental results and their relevance for interpreting contaminant occurrence under real farm conditions.

3. Results

MOSH and MOAH were detected in both feed and milk samples collected from the farms analyzed. The results describe the variability of the occurrence of contaminants within and between farms and do not imply direct transfer relationships.

The concentrations of MOSH and MOAH in feed samples varied between farms, with values covering wide ranges (Table 1). Farm 3 showed the widest range; MOSH ranged from 16.9 to 81.4 mg/kg, with a median of 35.5 mg/kg, and the central half of the distribution was between 27.0 and 54.1 mg/kg. MOAH also varied widely in Farm 3, from 0.0 to 4.6 mg/kg, with a median of 1.2 mg/kg, with the central half of the values between 0.3 and 2.8 mg/kg. In contrast, Farm 1 presented a relatively narrower variability (21.6–27.4 mg/kg). Median concentrations differed between the investigated farms, highlighting heterogeneous contamination patterns.

Table 1. Occurrence of MOSH and MOAH in feed samples across dairy farms.

Farm	Samples	Feed Category (No.)	ΣMOSH–Range (mg/kg) Min–Max	ΣMOSH (mg/kg)–Median (IQR *)	MOSH Subfractions (C-Range)	ΣMOAH–Range (mg/kg) Min–Max	ΣMOAH (mg/kg)–Median (IQR *)	MOAH Subfractions (C-Range)
Farm 1	2	Forage-based	21.6–27.4	24.5	C10–C20 dominant	1.2–1.6	1.4	C16–C25 dominant
Farm 2	5	Forage-based (2) Concentrate (2) Combined feed (1)	11.4–35.0	26.5 (23.3–28.1)	C10–C25 dominant	0.5–2.5	0.8 (0.6–1.7)	C16–C25; C35–C40 dominant
Farm 3	8	Forage-based (4) Concentrate (3) Combined feed (1)	16.9–81.4	36.5 (27.0–54.1)	C10–C35 dominant	0–4.6	1.2 (0.3–2.8)	C16–C25; C35–C40 dominant

* IQR: interquartile range (25th–75th percentile); for farms with $n < 4$, dispersion is reported as range (min–max).

MOSH and MOAH were also detected in milk samples, with varying concentration ranges (Table 2). The observed values also spanned a wide range, reflecting diverse contamination profiles. Samples from Farm 1 showed the widest range (3.2–13.1 mg/kg), with a median concentration of 8.7 mg/kg and an interquartile range of 6.0–10.9 mg/kg.

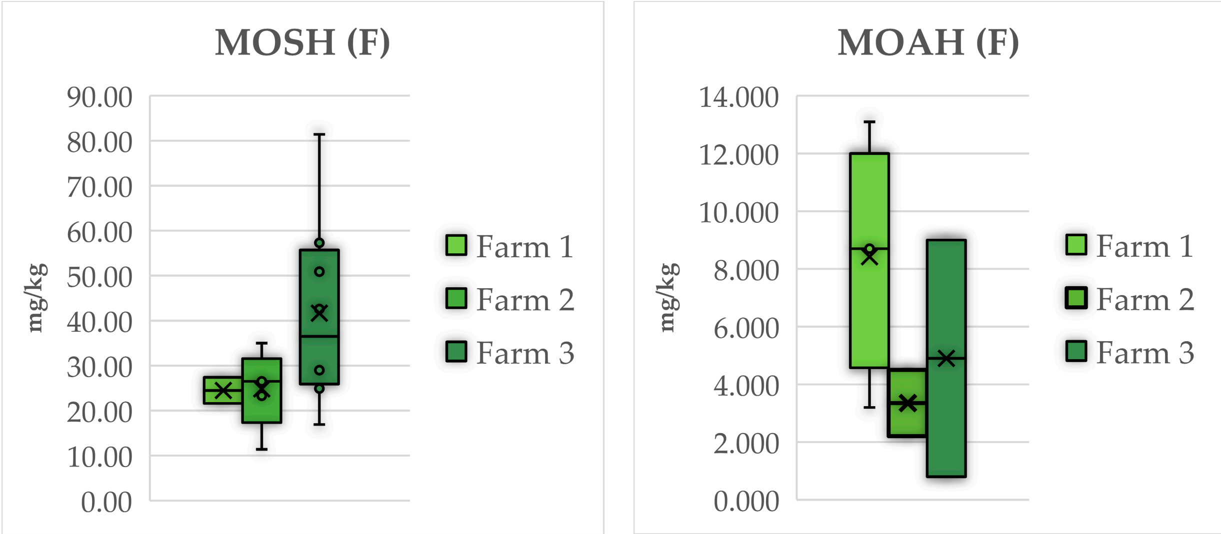
Table 2. Occurrence of MOSH and MOAH in milk samples across dairy farms.

Farm	Samples	ΣMOSH–Range (mg/kg) Min–Max	ΣMOSH (mg/kg)–Median (IQR *)	MOSH Subfractions (C-Range)	ΣMOAH–Range (mg/kg) Min–Max	ΣMOAH (mg/kg)–Median (IQR *)	MOAH Subfractions (C-Range)
Farm 1	4	3.2–13.1	8.7 (6.0–10.9)	C16–C20; C25–C35 dominant	0.0–5.35	3.0 (1.4–4.3)	C16–C35 dominant
Farm 2	2	2.2–4.5	3.4	C16–C25 dominant	0.0–4.0	2.0	C16–C25 dominant
Farm 3	2	0.8–9.0	4.9	C16–C35 dominant	0.0–4.45	2.2	C16–C25 dominant

* IQR: interquartile range (25th–75th percentile); for farms with $n < 4$, dispersion is reported as range (min–max).

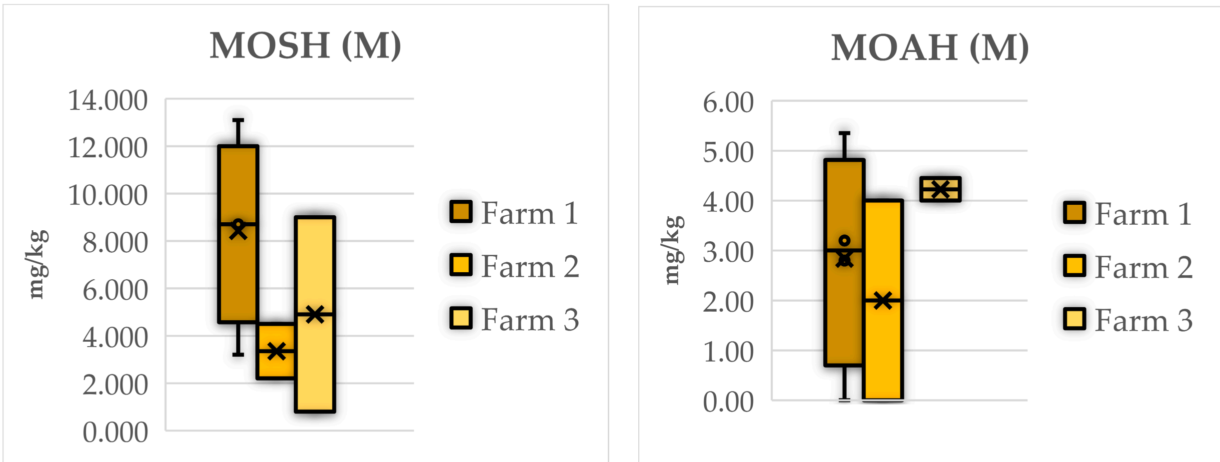
The boxplots show the dispersion of MOSH (a) and MOAH (b) concentrations within each farm, including deviations from the mean, for feed samples (Figure 2) and milk samples (Figure 3). The boxplots provide a descriptive overview of the data distribution, including median values, interquartile ranges and extreme values. Due to the limited and uneven number of samples collected from each farm, the data were primarily explored using descriptive statistics, and the results were interpreted in an exploratory manner rather than through formal statistical significance testing, correlation or regression analyses. For feed, Farm 3 shows a wider spread of MOSH concentrations compared to the other farms. The median values are visually different between farms, and the presence of extreme observations suggests heterogeneity of contaminants within farms. As shown in Figure 3, MOSH and MOAH concentrations in milk samples are also characterized by variable distributions between farms. Distinction in interquartile ranges and whisker lengths reflect uneven patterns of dispersion, while individual extreme values contribute to the observed heterogeneity.

The analysis of contaminant presence demonstrated, overall, wide variability. This variability was highlighted by broad value ranges, differing dispersions, and distinct distribution profiles between farms. The co-occurrence of contaminants in the analyzed matrices reflects consistent heterogeneity, characterized by fluctuations in central tendency and extreme values. The results therefore outline a pattern of uneven contaminant distribution within the analyzed production systems.



(**a**) (**b**)

Figure 2. Distribution of MOSH (**a**) and MOAH (**b**) concentrations in feed samples across dairy farms. Boxplots show median (horizontal line within the box), interquartile range (box), and extreme values (whiskers). The symbol "×" indicates the mean value, while circles represent outliers.



(**a**) (**b**)

Figure 3. Distribution of MOSH (**a**) and MOAH (**b**) concentrations in milk samples across dairy farms. Boxplots show median (horizontal line within the box), interquartile range (box), and extreme values (whiskers). The symbol "×" indicates the mean value, while circles represent outliers.

4. Discussion

The results obtained in the present study are characterized by wide distribution ranges of MOSH and MOAH contaminants, different medians, and variable intra-farm dispersion. These findings align with patterns described in the literature, which frequently report irregular non-uniform and variable distributions of MOSH/MOAH across agri-food systems [20,30]. The observed variability and uneven distribution patterns have been documented in previous studies, supporting the idea that contaminant occurrence is inherently heterogeneous within food production systems [19,30,33]. The interpretative framework applied to the occurrence patterns observed in this study is supported by the characteristic physico-chemical behavior of these compounds. The recurrent identification of MOSH and MOAH in feed and milk samples is consistent with their affinity for lipid containing substrates, a property that facilitates their presence across a wide range of plant and animal products. Comparable system-level patterns of contaminant occurrence have also been described for other classes of contaminants in animal-derived foods [43,44].

Mineral oil hydrocarbons can enter agri-food systems through multiple environmental and technological pathways, contributing to heterogeneous contamination patterns. Within the food chain, MOSH and MOAH are frequently associated with environmental pollution, inadequate harvesting or processing practices, the intentional use of mineral oil-based lubricants or release agents, accidental contamination events, and contact with materials containing mineral oils [45,46].

Background environmental contamination has been extensively investigated, particularly in relation to plant-derived matrices. Recent studies suggest that air pollution may be an important factor contributing to the occurrence of MOSH [47], although current evidence does not support environmental pollution as the sole determinant of MOSH/MOAH presence in substrates. For MOAH, the relationship with environmental contamination remains less clearly established, partly due to their lower release and oxidative transformation processes [47].

Technological inputs represent an additional and widely known source of variability. Technological interventions are known to influence the physicochemical profile of food matrices, indicating that processing conditions clearly contribute to shaping product quality [48]. Mineral oil-based lubricants used in agricultural machinery or food processing equipment, particularly when inadequately refined, can introduce complex mixtures of hydrocarbons into production environments [21,25,49]. Beyond accidental contamination, certain classes of mineral oils are legally authorized as processing aids, processing agents, or components of food contact materials, including release agents, paraffinic oils, packaging additives, and surface treatments [50–53]. Migration from packaging materials, printing inks, or transport media further contributes to the multiplicity of exposure pathways [45,54,55]. Agricultural activities may also represent important exposure routes, as mineral oils are incorporated into pesticide formulations and crop protection care treatments [56,57]. Therefore, plant-derived feed materials used in animal nutrition can act as indirect bearers within production systems [34]. The widespread detection of MOSH and MOAH in different food categories, including cereals, animal-derived products, fish and vegetable oils, shows the frequent occurrence of these contamination routes [14,28,50].

In this context, dairy matrices deserve special attention due to their nutritional relevance and lipid content. Although much of the existing literature has focused on dairy product contamination associated with packaging [32,58], the presence of mineral oil hydrocarbons in dairy production systems should be interpreted as part of a continuous interaction between technology and environment, characterized by multiple overlapping exposure sources. This perspective may explain the variability observed in the present study, without implicating a single dominant contamination pathway.

Direct evidence describing the metabolic transfer of MOSH and MOAH from animal feed to animal products remains limited [30]. However, research in aquatic production systems argues that feed composition may play a part in the hydrocarbon profiles detected in animal tissues, supporting the likelihood exposure pathways without establishing a universal transfer mechanism [34]. This underscores the need to interpret contaminant occurrence within a broader exposure framework rather than as a single linear process. Although the present study was not designed to demonstrate causal relationships between specific contamination sources and the measured MOSH and MOAH levels, the differences observed between the studied farms may plausibly reflect variations in environmental exposure and technological practices. The three dairy production systems differed in terms of their environmental context, mechanization level, feed management practices, and proximity to potential pollution sources. These contextual differences may contribute to the heterogeneous contamination patterns observed in feed and milk samples, as also suggested by previous studies investigating mineral oil hydrocarbons in agricultural and food production systems.

From a dietary exposure perspective, mineral oil hydrocarbons have been detected in a wide range of food categories, with particular attention given to products intended for sensitive populations, such as infant formula [21,59–61]. Although reported contamination events have raised public concern [62–64], the current scientific consensus emphasizes the cumulative nature of exposure and the need for continuous monitoring rather than definitive conclusions regarding health risk thresholds.

The toxicological assessment of mineral oil hydrocarbons remains challenging due to the heterogeneous composition of MOSH and MOAH mixtures. MOSH fractions are widely recognized for their capacity to accumulate in biological tissues, particularly in lipid-rich compartments, with potential histopathological associations under chronic exposure [50,65–67]. Attention regarding mineral oil hydrocarbons has focused mainly on the MOAH fraction, because of its comparatively higher toxicological relevance [45,59,65,66,68]. Although limits have not yet been established, previous perspectives have highlighted that the presence of contaminants in animal feed may have involvements beyond animal health, potentially influencing the perception of quality and safety of animal-derived foods [49].

The occurrence of MOSH and MOAH in feed and milk observed in the present study should be interpreted as part of a broader exposure chain characteristic of modern agri-food systems. The findings do not demonstrate metabolic transfer but are in accordance with existing evidence indicating that lipid-related contaminants can persist in production environments, strengthening the importance of integrated monitoring. In environmental terms, the presence of mineral oil hydrocarbons in feed and milk highlights the sensitivity of dairy production systems to environmental and technological factors. The analytical assessment of MOSH and MOAH remains technically challenging due to the complicated structure of these compounds and the low selectivity needed to distinguish them from non-mineral hydrocarbons [69]. However, methodological advances and appropriate analytical frameworks, in particular those described in JRC guidelines and standardized LC-GC-FID approaches, provide an increasingly strong basis for monitoring agri-food products [14,45,68].

The evolving regulatory provisions concerning mineral oil hydrocarbons emphasize the importance of shifting contamination management from isolated product control toward system-wide surveillance. Although mandatory limits are still under development, European recommendations and risk assessments highlight precautionary monitoring and data collection, underscoring the need for dynamic quality management throughout the food chain [14,28,50]. In dairy production systems, feed represents a critical link between environmental exposure and animal output. Preventive steps targeting harvesting, storage, equipment maintenance, packaging materials, and processing conditions can limit contaminant occurrence before it propagates through subsequent production stages. This approach is prioritizing performance, productivity, and risk reduction over corrective interventions, according sustainability principles.

The conceptual framework projected in this study supports a systems-based interpretation in which the animal functions as a biological modulator rather than a passive transfer medium. Metabolic processes, retention dynamics, and elimination pathways introduce variability and illustrate the importance of integrated monitoring that considers environmental, technological, and biological factors. Overall, these considerations suggest that sustainable dairy production could seriously benefit from a shift in focus toward preventive monitoring and intersectoral coordination. While additional research is necessary to elucidate the specific mechanisms of exposure, the current findings and conceptual model offer a pragmatic foundation for pinpointing control points and enhancing adaptability within dairy production systems.

In terms of methodological limitations and considerations, it should be noted that the present study did not aim to demonstrate a direct transfer of individual contaminants from feed to milk, nor was any attempt made to establish chemical correlations between the two matrices. Instead, the work is based on a descriptive analysis of field data aimed at characterizing contaminant presence under real farm conditions. The simultaneous detection of MOSH and MOAH in feed and milk supports the plausibility of exposure pathways in accordance with the proposed conceptual framework, without implying linear transfer mechanisms. Accordingly, the conceptual model should be interpreted as an integrated representation of exposure and presence across the four functional compartments considered in the study, rather than as evidence of causality. Another limitation of the present study is the relatively small number of samples collected from some of the investigated farms. This constraint reflects the exploratory nature of the field investigation and practical limitations associated with sampling under real farm production conditions. Consequently, the results should be interpreted primarily as an exploratory characterization of MOSH and MOAH occurrence rather than as statistically generalizable patterns.

The results of this study highlight the importance of continuous and coordinated monitoring of mineral oil hydrocarbons in dairy production systems, especially in relation to environmental exposure and feed management. The analysis of data obtained under real farm conditions can improve the understanding of variability patterns and support the development of practical mitigation measures. Sustainable dairy production means considering contamination as part of the system. Contaminant monitoring should not be conducted in isolation but should be included in broader farm sustainability assessments, alongside resource consumption and environmental impact, to provide a comprehensive perspective on production safety. Future research should clarify furthermore contamination pathways, biological responses within the animal, and points at which practical interventions can be applied to help farms prevent risks and operate more stably. Future studies including larger sample sets would be necessary to further validate the observed contamination trends.

5. Conclusions

This study assessed the presence of mineral oil hydrocarbons in feed and milk within dairy production systems based on real-world data and highlighted the variable nature of contaminant occurrence across farms. Rather than indicating a simple linear transfer, the results support the view that contaminant presence reflects a complex interaction among environmental and technological exposures, feed management, and biological processes.

The proposed conceptual framework considers contaminant emergence as a result of interrelationships within the production system, in which the environment, feed, animals and milk function as interconnected compartments that influence contaminant dynamics. This framework facilitates the interpretation of differences in contaminant levels without claiming direct causality, while providing a practical basis for understanding observations made under real production conditions. From a sustainability perspective, the results underscore the importance of monitoring and preventive management at the farm level to limit contaminant pressure before it affects subsequent stages of production. Considering the potential transfer of mineral oil hydrocarbons from feed to animal-derived products, it is recommended that monitoring strategies be strengthened particularly during feed production and harvesting, storage of feed materials, the use and maintenance of machinery, and during milk collection and processing. Addressing contamination as a system-level issue, rather than a solely a product-level concern, encourages more resilient and adaptable dairy production practices. Overall, the study links analytical observations with a system-level understanding of contaminant emergence. By combining real data with a conceptual model, the study supports improved monitoring, management, and future research aimed at enhancing the safety and sustainability of dairy production.

Author Contributions: Conceptualization, M.M. and E.-I.F.; methodology, M.M. and E.-I.F.; software, M.M.; validation, I.M.P.; formal analysis, M.M.; investigation, M.M. and E.-I.F.; resources, E.-I.F.; data curation, I.M.P.; writing—original draft preparation, M.M. and E.-I.F.; writing—review and editing, M.M. and E.-I.F.; visualization, I.M.P.; supervision, I.M.P.; project administration, M.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Acknowledgments: This study is part of a research initiative on feed contamination and contaminant transfer into animal-derived products, conducted through collaboration between the Iasi University of Life Sciences (Romania) and the University of Udine (Italy). The authors acknowledge the Food Chemistry Laboratory team for providing facilities, resources, and technical support.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

JRC	Joint Research Center
LC-GC-FID	Liquid Chromatography–Gas Chromatography–Flame Ionization Detection
MOH	Mineral Oil Hydrocarbons
MOAH	Mineral Oil Aromatic Hydrocarbons
MOSH	Mineral Oil Saturated Hydrocarbons

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https://doi.org/10.3390/su18062889