CADMIUM CONTAMINATION IN COW'S MILK: SOURCES, OCCURRENCE AND IMPLICATIONS FOR FOOD SAFETY

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Abstract

Cadmium is a toxic heavy metal with a high bioaccumulation capacity, the presence of which in milk raises food safety and public health concerns. The aim of this article is to analyze the existing data from the specialized literature regarding the sources of cadmium contamination, the transfer mechanisms in the bovine body and the levels detected in milk. A literature review was conducted using studies published in different geographical regions. Data sources included survey articles, field analyses and systematic reviews focused on heavy metal pollution.

The available studies report a significant variability in the level of contamination influenced by exposure routes, region, growing environment and diet, some values approaching or even exceeding the legal limits allowed at European and international level. The highest cadmium concentrations were reported in areas with heavy traffic or industrial activity, with most studies confirming the wide variation in contamination and its correlation with the degree of urbanization and industrialization. The cadmium contamination of milk reflects the direct influence of anthropogenic factors and environmental pollution on animal production.

Key words: *cadmium, heavy metals, food contamination, food safety.*

INTRODUCTION

Considered by many authors as an almost perfect and complete natural food [1,2], milk is one of the most valued products of animal origin and is frequently associated with a balanced diet and high dietary quality [3,4]. Due to its nutritional value, high bioavailability of essential nutrients, and complex composition, milk constitutes an important component of the daily diet for infants, children, the elderly, and convalescents. It also represents a major source of animal protein for many vegetarians, a population that is growing worldwide [5-7]. Although consumption levels vary depending on dietary habits and product availability, milk remains among the population's favorite foods, being associated both with the prevention of chronic diseases and the maintenance of overall health [8,9].

However, despite its nutritional value, milk is susceptible to contamination and can accumulate a wide range of chemicals originating from the environment or from technological processes. Studies by Radzyminska et al. [10] and Avancini et al. [11] indicate that some of the most toxic compounds found in milk include persistent organic pollutants (such as pesticide residues and by-products of incomplete combustion), heavy metals, radionuclides, veterinary drugs, aflatoxins, mycotoxins, as well as nitrates and nitrites. Similarly, Aytenfsu et al. [12] attributed the presence of these contaminants to environmental pollution, uncontrolled pesticide use, or inappropriate drug administration, highlighting the potential risks to milk safety.

Globally, over six billion people consume milk and dairy products [13,14], making the monitoring of their quality and

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safety a continuous concern at the international level. However, most surveillance programs focus primarily on microbiological contaminants and drug residues, while environmental pollutants-such as heavy metals and persistent organic compounds-are often inadequately monitored, despite their significant potential impact on public health.

Heavy metals represent a particularly important category of environmental pollutants due to their persistence, bioaccumulation potential, and high toxicity to living organisms [15]. These properties make their presence, even at low concentrations, a significant risk to both ecosystems and human health, as also highlighted by Aprile & De Bellis [16] in their analysis of the ecological impact of heavy metals.

Among heavy metals, cadmium (Cd) is one of the most toxic and hazardous inorganic contaminants, ranking as the seventh most toxic heavy metal [17]. Toxicologically, Cd exhibits a high potential for bioaccumulation along food chains, being absorbed by plants and subsequently transferred to animals and humans through food consumption. Exposure to cadmium can lead to acute or chronic poisoning, affecting the kidneys, liver, and bones, interfering with calcium and zinc metabolism, and demonstrating carcinogenic effects in experimental studies [17].

The presence of cadmium in the environment and its potential transfer to food, including milk, represents a major concern for food safety and public health.

Contamination of cow's milk with heavy metals, particularly cadmium, is a current issue with direct implications for consumer safety. However, the literature highlights significant gaps in the assessment of cadmium levels in raw milk and their correlation with contamination sources. Most studies focus on microbiological contaminants or drug residues, while inorganic pollutants remain insufficiently investigated.

Given cadmium's persistence and bioaccumulation potential along the food chain, examining its presence in milk helps fill existing knowledge gaps and underscores the need to strengthen monitoring measures to protect consumers.

MATERIAL AND METHOD

This paper presents a narrative review of the specialized literature on cadmium (Cd) contamination in cow's milk, with the primary objective of synthesizing existing data on contamination sources, reported levels, and implications for food safety and public health. Studies published between 2000 and 2025 were analyzed, selected from international scientific databases including ScienceDirect, Scopus, PubMed, SpringerLink, and Google Scholar, using combinations of the following keywords: "cadmium," "milk contamination," "heavy metals in milk," "toxic metals," "food safety," "bioaccumulation," "cattle feed," and "environmental pollution."

The selection process included experimental or monitoring studies measuring cadmium levels in raw milk or dairy products, review articles, reports by international authorities (EFSA, WHO, FAO), and studies evaluating the relationship between environmental contamination, animal feed, and the transfer of heavy metals into milk.

Scientifically unverified sources, articles with incomplete data, or studies that did not explicitly report the cadmium determination method and detection limits were excluded. For each selected study, relevant information was extracted, including: country and year of publication; analytical method used, minimum, maximum, and average Cd concentrations; sample type (raw milk, pasteurized milk, dairy products); potential contamination sources (feed, water, air, soil, technological factors); and reporting of results in comparison with limits established by European or international regulations.

The data were analyzed comparatively to identify general trends (typical values by geographical region), determinants of contamination, and potential methodological differences explaining the variations reported in the literature. The results were interpreted using descriptive and comparative analyses, focusing on the potential exposure of consumers, correlations between environmental and milk contamination, and the toxicological relevance of the detected levels in relation to reference values established by EFSA and WHO (TWI/PTWI for Cd). Findings were synthesized objectively, with the aim of identifying knowledge gaps and future research directions in the field of food safety. Bibliographic documentation was conducted using open-access articles and institutional academic platforms, prioritizing studies indexed in international databases and official reports published by European and international regulatory authorities.

RESULTS AND DISCUSSIONS

Cadmium is a by-product of the zinc industry, primarily resulting from the smelting and refining of non-ferrous metals. Once released into the environment, it is highly persistent, accumulating in soils and sediments where it can remain bioavailable for extended periods. Cadmium can enter cow's milk through multiple routes, with the main ones being feed, water, and contaminated soil or air [10,11]. Khan et al. [18] identified rapid industrialization and increased urbanization as major contributors to heavy metal pollution, which accelerate their environmental transport and bioavailability. Mackay et al. [19] reported higher heavy metal concentrations in urban areas compared to rural ones, highlighting heavy vehicular traffic as a significant source of exposure. Singh [20] emphasized that it is nearly impossible for living organisms to exist in an environment entirely free of heavy metals, as they constantly enter through water, food, or air, and both acute and chronic exposures can produce toxic effects in animals and humans. Additionally, Aprile & De Bellis [16] noted that heavy metals can originate from agricultural, chemical, household, or technological sources (Fig. 1), each presenting specific toxicological profiles depending on the origin.

Feed is the primary source of cadmium exposure, as plants grown in soils with high Cd concentrations can bioaccumulate the metal, which is then ingested by cattle. Cadmium levels vary depending on the type of feed, with green plants and silage potentially containing different concentrations compared to concentrated feeds. In this context, feed and water consumed by cattle represent the main routes of cadmium transfer along the food chain, posing risks to both animal health and, consequently, to consumers of dairy products (Table 1).

Cadmium absorption in cattle occurs primarily in the intestine, and its distribution in the body is determined by the metal's ability to bind to specific proteins, such as metallothioneins, as well as by the degree of accumulation in storage organs like the kidneys and liver [17, 21]. Transfer of cadmium to milk constitutes a secondary excretion pathway—less significant than accumulation in major organs but relevant for the exposure of dairy consumers. Excretion mechanisms include urinary and fecal elimination, as well as secretion into milk, which can be influenced by the physiological characteristics of the animal.

Studies suggest that the stage of lactation has a direct effect, with higher Cd transfer occurring during the first weeks after calving, when milk production and mineral metabolism are elevated. The age of the cows also affects long-term heavy metal accumulation, with younger cows generally exhibiting lower transfer into milk compared to adults, who tend to accumulate more in storage organs. Health status is another important factor, as liver or kidney disorders can alter both cadmium retention and elimination rates.

Milk thus acts as an additional detoxification pathway, although the amount of cadmium excreted is relatively small compared to its accumulation in internal organs.

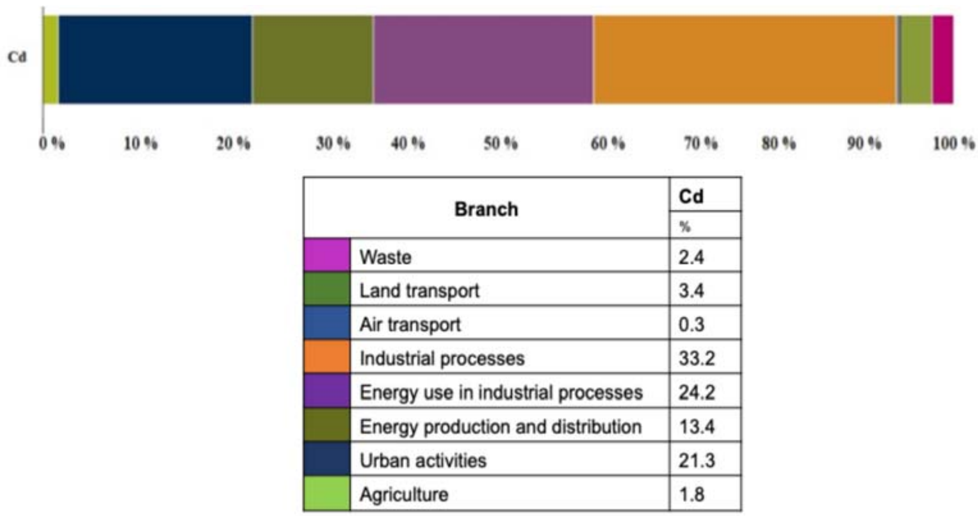

Fig. 1 Main sources of Cd contamination

Table 1 Distribution of Cd at different trophic levels

Substrate	soil	water	feed	milk	*References*
	mg kg^{-1}	*mg L^{-1}*	*mg kg^{-1}*	*mg L^{-1}*	
Cd	0.75 – 8.36	0.34 – 2.8	0.10 – 1.44	0.003 – 0.01	*[22]*
	1.9 – 6.8	ns.	1.1 – 4.1	0.04 – 0.3	*[23]*

Table 2 Methods for assessing the presence of Cd in different matrices

Methods	Heavy metals	Region	*References*
Infrared Spectrometry	Fe, Zn, Cu, Mn, Se, Al, **Cd**, Cr, Pb	Spain	*[24]*
Potentiometric stripping	**Cd**, Pb, Cu	Serbia	*[25]*
Flame atomic absorption spectrophotometry	Al, Mn, Ni, Cu, **Cd**, Pb, Cr, Fe, Zn	Niger	*[26]*
	Cd, Ni, Fe, Zn, Cu	Slovenia	*[27]*
	Cd, Cu, Pb, Fe, Zn	Egypt	*[28]*
	Pb, **Cd,** Zn, Cu, Fe		*[29]*
	Pb, Cu, **Cd**, Zn	**Romania**	*[22]*
Inductively coupled plasma mass spectrophotometry	Zn, Se, Cr, As, **Cd**, Pb	Koreea	*[30]*
Atomic absorption spectrometry with voltammetric analyzer	Pb, **Cd**, As, Hg	Kazakhstan	*[31]*

Cd is a heavy metal with no biological role, capable of disrupting normal physiological functions even at very low concentrations [32].

Unlike essential metals, cadmium has no metabolic function and is characterized by high environmental persistence and a strong potential for bioaccumulation along the food chain [33] (Fig. 2).

Contamination of milk with cadmium represents a significant threat to human health, as the metal can be transferred from animals to consumers, and its elimination from the human body is very slow.

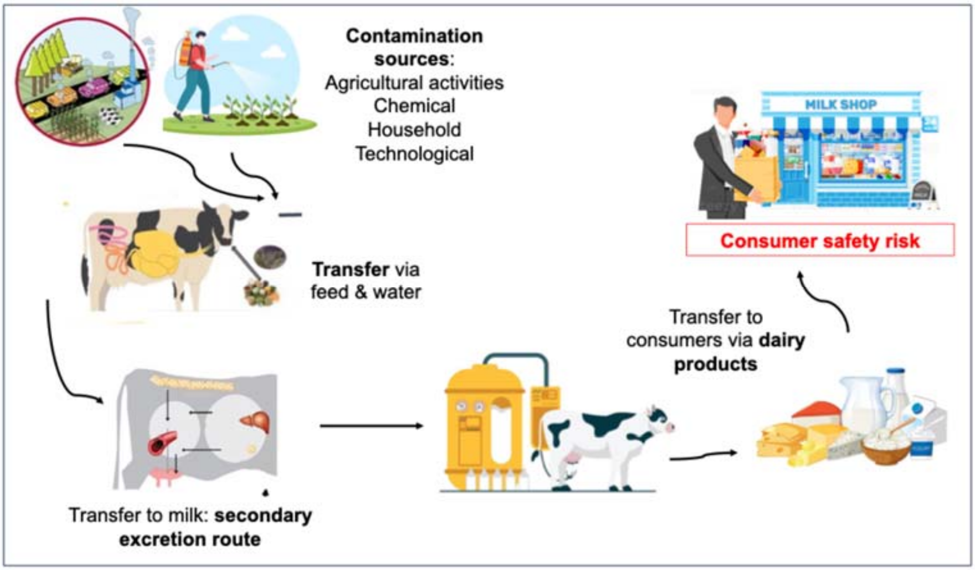

Fig. 2 Cd transfer and bioaccumulation in the food chain

Table 3 Levels of Cd detected in milk

	Concentration in milk		References
	Min. – Max.	Average	
	µG/mL		
Cd	0.062 – 10.1	1.520	*[34]*
	0.045 – 0.310	-	*[35]*
	0.088 – 0.167	0.153	*[30]*
	0.003 – 0.009	0.007	*[36]*
	0.015 – 0.059	0.026	*[37]*
	0.35 – 2.85	-	*[23]*
	0.07 – 0.08		*[38]*
	0.095 – 10.62	2.631	*[26]*
	0.002 – 0.009	0.004	*[39]*
	0.01 – 0.08	-	*[40]*
	0.027 – 0.086	0.055	*[41]*
	-	0.84	*[42]*
		0.62	*[43]*
		0.01	*[44]*

Reported Cd levels in milk vary depending on the region, proximity to industrial or urban sources, and the type of feed provided to cattle. Additionally, the analytical method used (Table 2) affects detectable limits; nevertheless, available data indicate that, although Cd is generally present at low concentrations, it has the potential for chronic accumulation.

Specialized research on cadmium contamination of milk [45-48] has shown that Cd levels in milk are not constant, varying according to exposure routes, environmental conditions, type of feed and animal nutrition, cow breed, and stage of lactation. These factors influence both the absorption of the metal in the bovine body and its transfer to milk, resulting in significant differences between farms and geographical regions. Average Cd concentrations in raw milk are generally below the limits set by international regulations; however, certain industrial areas or regions with cadmium-rich soils may exhibit exceedances.

Recent studies on cadmium contamination of milk have reported significant variations in levels depending on the degree of environmental pollution (Table 3). Over the past decade, the highest concentrations were observed in Pakistan, where Iftikhar et al. [49] found values of up to 0.7 mg/L in milk samples collected from an urban area exposed to heavy vehicular traffic. Similarly, in Turkey, Bigucu et al. [50] reported concentrations of 0.39 mg/L in milk from cows raised near industrial zones and busy roads. These cases highlight the direct impact of urban and industrial pollution on cadmium levels in cow's milk, emphasizing the importance of monitoring and managing associated public health risks.

The European Union sets maximum limits for cadmium in cow's milk at 0.02 mg/kg [51], and international bodies such as WHO/JECFA provide reference values for the tolerable weekly intake (TWI). Monitoring of cadmium in milk is conducted through national food safety surveillance programs, but most efforts focus primarily on microbiological contaminants and drug residues. This underscores the need to strengthen surveillance of inorganic pollutants, particularly in areas with a high risk of industrial or agricultural contamination.

Reducing cadmium exposure in the food chain requires multiple strategies. At the feed level, cultivating plants with low bioaccumulation potential and limiting the use of contaminated phosphate fertilizers are recommended. Soil and irrigation water management, through soil improvement and water filtration, also helps reduce metal transfer to plants. At the farm level, practices such as crop rotation, avoiding grazing in contaminated areas, and dietary supplementation with minerals like Ca, Zn, and Fe can decrease Cd absorption in cattle. The implementation of these measures, combined with continuous monitoring of Cd levels, is essential to protect consumers and ensure food safety.

CONCLUSIONS

Cadmium is a heavy metal with no biological role, characterized by high persistence and bioaccumulation potential, making it a significant threat to human health when present in milk. The studies reviewed indicate that Cd levels in milk vary considerably depending on environmental factors, type of feed, physiological status of the animals, and proximity to industrial or urban pollution sources. In some regions, reported concentrations have approached or even exceeded international regulatory limits, underscoring the potential risk to consumers.

These findings emphasize the importance of continuous monitoring of cadmium in dairy products, particularly in areas with high pollution risk. Implementing rigorous surveillance programs and adopting preventive measures at both farm and food chain levels are essential to protect consumers and ensure food safety.

In the long term, research on the transfer of cadmium and other heavy metals into milk enhances understanding of bioaccumulation and excretion mechanisms and supports the development of effective strategies to reduce contamination, thereby directly contributing to public health protection.

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