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MILK SPOILAGE AND CONTAMINATION ACROSS THE DAIRY CHAIN: MICROBIAL CAUSES, SAFETY CONCERNS, QUALITY DETERIORATION, AND ECONOMIC CONSEQUENCES, WITH REFERENCE TO INDIA

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ABSTRACT

Milk combines high nutritional value with a marked susceptibility to microbial deterioration. Its high water activity, near-neutral pH, and supply of proteins, carbohydrates, fats, vitamins, and minerals favour microbial growth (Gaucheron, 2011), and contamination can enter at almost any point in the dairy chain, including milking, handling, storage, transport, and processing (Shuba et al., 2025; Washaya et al., 2022). Refrigeration and heat treatment improve keeping quality, but neither guarantees it. In raw and pasteurized fluid milk, cold-tolerant Gram-negative bacteria, particularly *Pseudomonas* spp., are major contributors to quality loss because they release extracellular proteases and lipases that can remain active after pasteurization (Machado et al., 2017; de Oliveira et al., 2015). Gram-positive spore-formers, especially *Bacillus* and *Paenibacillus*, pose a different challenge because their endospores withstand conventional heat treatment (Gopal et al., 2015). Lactic acid bacteria, Enterobacteriaceae, *Clostridium* spp., and spoilage fungi add product-specific defects such as souring, gas formation, and coagulation (Garnier et al., 2017; Ledenbach& Marshall, 2009).The resulting defects, which include off-flavours, rancidity, bitterness, coagulation, sediment, and shortened shelf life, carry substantial economic consequences: rejected raw milk, discarded product, lost saleable life, and higher spending on testing, cleaning, and sanitation. Global losses attributed to milk spoilage have been estimated at approximately USD 5–6 billion a year (Lu & Wang, 2017); in the United States, dairy accounted for about 17% of the value of food lost or wasted at retail and consumer level (Buzby et al., 2014; Gunders & Bloom, 2017). The issue is especially pertinent to India, the world's largest milk producer (247.87 million tonnes in 2024–25), where about two-thirds of marketable milk passes through the unorganised sector. Reported post-harvest milk losses of roughly 0.5–1.4% of production correspond to an indicative ₹3,000–8,000 crore a year, before allowing for quality downgrading, mastitis, and spoilage that goes unrecorded in informal channels.

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1. Introduction: A Nutritious Food That Spoils Easily

1.1 The nutritional paradox of milk

Milk and dairy foods supply high-quality protein and a range of essential minerals, including calcium, potassium, phosphorus, magnesium, and zinc, together with vitamins such as riboflavin, niacin, vitamin B6, and vitamin B12 (Gaucheron, 2011). This contribution makes milk important both as a drink and as the starting material for a wide variety of foods. Yet the same nutrient-rich composition makes it an ideal medium for microbial growth.

Microorganisms may enter milk from the farm environment and at later stages, including milking, collection, transport, storage, processing, and packaging. Maintaining quality therefore requires consistent control across the whole dairy chain; no single treatment can compensate for weaknesses at every other stage (Fusco et al., 2020). The organisms that dominate, and the defects they cause, vary with processing and storage conditions. Pasteurized milk, cheese, yogurt, and other cultured products generally face different spoilage pressures from long-life products such as ultra-high-temperature (UHT) milk and dairy powders. Bacteria (both Gram-negative and Gram-positive), yeasts, and moulds can break down proteins, fats, and lactose, generating unwanted odours, flavours, pigments, gas, and changes in texture (Ledenbach & Marshall, 2009). Such deterioration can make a product unacceptable and adds to dairy-related food waste.

1.2 Spoilage is not the same as foodborne disease

Microbial spoilage must be distinguished from foodborne infection and intoxication. Spoilage organisms primarily affect a product's sensory properties, chemical composition, or processing performance. Pathogens, by contrast, may cause illness even when the milk looks and tastes normal. The distinction is not absolute, however: some microorganisms associated with deterioration, such as *Bacillus cereus*, also have food-safety implications.

Contamination of raw milk can arise from within the animal or from its surroundings. Endogenous contamination occurs when pathogens reach the mammary gland through the bloodstream during systemic infection, or through udder infections such as mastitis (Zastempowska et al., 2016). Exogenous contamination takes place during or after milking, when milk contacts faecal material, the skin or outer surfaces of the udder and teats, contaminated equipment, handlers, or the farm environment. The health consequences depend on the organism involved and the susceptibility of the person exposed. Young children, older adults, pregnant women, and immunocompromised people are more likely to experience severe disease, particularly from *Listeria monocytogenes* (Verraes et al., 2015).

Foodborne illness remains a major public-health concern worldwide. In 2015, the World Health Organization estimated that contaminated food causes illness in roughly 600 million people each year and contributes to 420,000 deaths, including 125,000 among children under five (WHO, 2015). Outbreaks linked to milk and dairy products continue to occur despite quality-control measures and the use of pasteurization or UHT treatment.

1.3 Parasites: relevant to safety, not to spoilage

Toxoplasma gondii is a protozoan parasite that serological and molecular investigations have detected in raw milk from goats, sheep, cattle, buffaloes, and camels in Egypt and Iran, with some studies reporting comparatively higher contamination in goat milk (Saad et al., 2018; Ahmed et al., 2014; Nasiri et al., 2025; Elbarbary et al., 2026). Consumption of unpasteurized milk has also been associated with *T. gondii* seropositivity in human populations, including pregnant women (Markon et al., 2020; Rehman et al., 2020). This evidence makes the parasite relevant to food safety and public health, but not to milk deterioration (Marín-García et al., 2022). It is therefore not considered further in the spoilage sections that follow.

1.4 The Indian dairy context

India is the world's largest milk producer. Output reached 247.87 million tonnes in 2024–25, a rise of 3.58% over the previous year (Department of Animal Husbandry and Dairying [DAHD], 2025), and the country accounts for roughly a quarter of world production (24.64% in 2021–22; Kumar & Tirath, 2026). Milk is also the largest component of the livestock economy, contributing 65.9% of the value of livestock output in 2023–24 (Ministry of Statistics and Programme Implementation [MoSPI], 2025). Table 1 summarizes the sector indicators most relevant to spoilage.

Table 1. Indian dairy sector indicators relevant to milk spoilage

Indicator	Value	Source
Milk production, 2024–25	247.87 million tonnes (+3.58% over 2023–24)	DAHD (2025)
Share of world production	About 24.6% (2021–22)	Kumar & Tirath (2026)
Per capita availability	485 g per day	DAHD (2025)
Share of output marketed	About 63%; the remaining 37% is retained by producer households	Pashu Sandesh (2026)

Indicator	Value	Source
Marketable surplus handled by the organised sector (cooperatives and private dairies)	About 32%	Pashu Sandesh (2026)
Marketable surplus handled by the unorganised sector (vendors, direct sales, small traders)	About 68%	Pashu Sandesh (2026)
Milk's share of livestock output value, 2023–24	65.9%	MoSPI (2025)
Approximate value of milk output, 2023–24	About ₹6.1 lakh crore	MoSPI (2025)
Milk samples failing one or more FSSAI quality parameters (fat, SNF, added sugar, etc.), 2018 survey of 6,432 samples	39%	FSSAI (2018)

DAHD, Department of Animal Husbandry and Dairying; MoSPI, Ministry of Statistics and Programme Implementation; FSSAI, Food Safety and Standards Authority of India; SNF, solids-not-fat.

Several features of this system shape how spoilage develops. Production is spread across a very large number of small producers, and about 68% of the milk that reaches the market is handled outside the organised sector, where continuous refrigeration, routine microbiological testing, and quality-based payment are less likely to be in place (Pashu Sandesh, 2026). High ambient temperatures for much of the year further shorten the interval before microbial growth becomes consequential. The most extensive recent assessment of milk quality in India, the 2018 National Milk Quality Survey of the Food Safety and Standards Authority of India (FSSAI), points in the same direction. It examined 6,432 samples of raw (59%) and processed (41%) milk and found that 39% failed at least one quality parameter. Safety non-compliance was lower, but aflatoxin M1 exceeded the permitted limit in 5.7% of samples and antibiotic residues in 1.2% (FSSAI, 2018).

Figure 1 provides a graphical overview of the chain, the microbial groups encountered at each stage, and the downstream consequences discussed throughout.

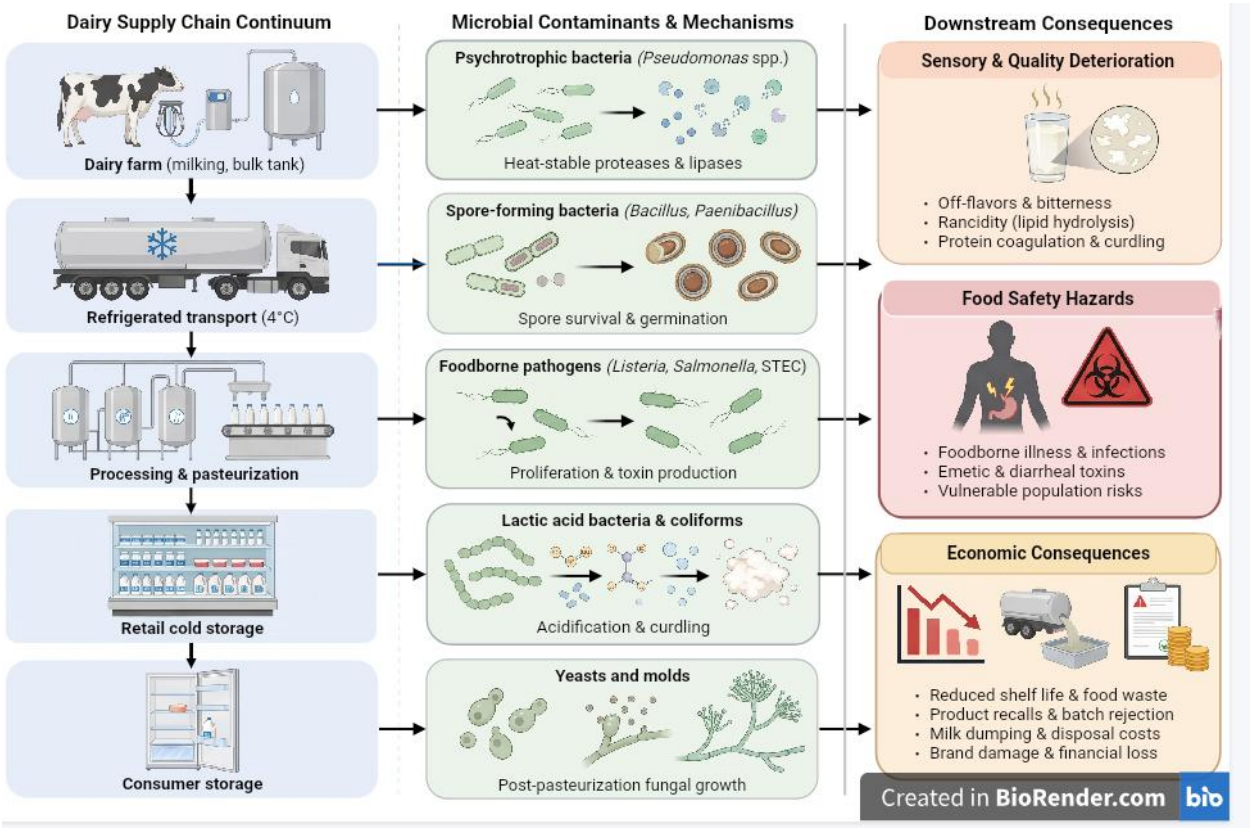


Figure 1. Overview of microbial contamination and its consequences along the dairy supply chain. Left: stages from the dairy farm to consumer storage. Centre: the principal microbial groups and mechanisms associated with each stage. Right: the downstream consequences for sensory quality, food safety, and economics.

2. Where Spoilage Begins: Sources and Routes of Contamination

Contamination can enter milk at several points between the udder and the consumer. This section follows those entry points from the farm environment through cleaning systems, equipment, and refrigerated transport.

2.1 The farm environment

The farm environment offers numerous opportunities for microorganisms to enter milk. Soil, manure, animal bedding, feed, dust, and water can all act as reservoirs, and the resulting raw-milk microbiota is complex (Quigley et al., 2013). Spore-forming bacteria are especially associated with these sources because their spores are widespread and tolerate many environmental stresses (Dai et al., 2024; Sun et al., 2025). When udder hygiene is poor, organisms can be transferred directly during milking. Inadequately cleaned equipment and milk-contact surfaces create another route, allowing microorganisms to persist and contaminate later batches (Velázquez-Ordoñez et al., 2019).

2.2 Water and cleaning systems

Water of poor microbiological quality can contaminate milk directly or introduce organisms during washing and cleaning. Removing visible milk residues is not enough if microorganisms remain attached to equipment surfaces (Zastempowska et al., 2016). Surviving cells can establish biofilms, and repeated contact with residual milk provides conditions that support their persistence and development.

2.3 Milking and storage equipment

Equipment that contacts milk forms a critical link between the farm environment and the product. *Pseudomonas* spp. and spore-forming bacteria can remain on these surfaces and repeatedly seed new batches (Shalini & Gurunathan, 2025). Organisms embedded in biofilms are particularly difficult to remove because attached cells and spores often tolerate environmental and cleaning stresses better than free-living cells (Yalew et al., 2024; Dai et al., 2024). Biofilms formed by *Pseudomonas* in dairy-processing facilities are therefore an important source of recurring contamination (Marchand et al., 2012).

2.4 Transportation and refrigerated storage

The time milk spends between milking and processing can strongly influence its microbial profile. Chilling slows bacterial multiplication, but it does not stop psychrotrophic organisms from growing. When refrigerated storage is prolonged, these cold-tolerant bacteria can become increasingly dominant. Zhang et al. (2020) found that extended storage changed the bacterial diversity of raw milk and favoured psychrotrophs capable of producing heat-stable proteases and lipases.

In smallholder-dominated systems, the interval between milking and chilling is often the weakest point. Studies of smallholder dairy value chains in Africa have documented high bacterial loads in raw milk at collection and sale (Owusu-Kwarteng et al., 2020; Washaya et al., 2022), and similar constraints are likely wherever milk is moved by hand or by vehicle from many small farms in warm conditions without continuous cooling. In India, where about two-thirds of marketable milk is handled by the unorganised sector (Pashu Sandesh, 2026), delays before chilling and the absence of a continuous cold chain are therefore central to the spoilage risk.

3. The Organisms Behind Spoilage

The organisms involved in milk deterioration differ in their behaviour and in the products they affect. Gram-negative bacteria are particularly important in the spoilage of raw and pasteurized fluid milk. Other contributors include Gram-positive spore-formers, lactic acid bacteria, Enterobacteriaceae, *Clostridium* spp., yeasts, and moulds; their effects depend on the product and its storage conditions. Table 2 summarizes the principal groups.

Table 2. Principal bacterial (and fungal) groups associated with milk spoilage (Accettulli & d'Amelio, 2025)

Group	Representative organisms	Main spoilage characteristics	Common quality defects
Psychrotrophic Gram-negatives (*Pseudomonas* spp.)	*P. fluorescens*, *P. fragi*, *P. lundensis*	Extracellular proteases and lipases; biofilm formation	Bitter taste, rancid flavour, instability, reduced shelf life
***Bacillus* spp.**	*B. licheniformis*, *B. cereus*, *B. subtilis*	Spore formation, proteolysis, lipolysis	Coagulation, off-flavours, reduced shelf life
***Paenibacillus* spp.**	*P. odorifer* and related species	Psychrotrophic growth, spore formation	Premature spoilage, quality deterioration
Lactic acid bacteria	*Lactococcus*, *Lactobacillus*, *Leuconostoc*	Lactose fermentation	Souring and acidification
Enterobacteriaceae	*Enterobacter*, *Citrobacter*, *Klebsiella*	Fermentation and gas production	Off-odours, gas, acidification
***Clostridium* spp.**	*C. tyrobutyricum* and related species	Anaerobic fermentation	Gas formation and product defects (mainly cheese)

Group	Representative organisms	Main spoilage characteristics	Common quality defects
Spoilage fungi	*Penicillium*, *Aspergillus*, *Mucor*, spoilage yeasts	Growth at low pH and low water activity	Yeasty odour, bitterness, gas, mould growth (cheese, butter, yogurt)

3.1 Pseudomonas and other psychrotrophic Gram-negative bacteria

Cold-tolerant *Pseudomonas* species, including *P. fluorescens*, *P. fragi*, and *P. lundensis*, are frequently recovered from spoiled milk. Other psychrotrophic Gram-negative genera, such as *Acinetobacter*, *Enterobacter*, and *Serratia*, may also be involved. *Pseudomonas* is especially significant in refrigerated raw milk because it combines the ability to grow at low temperatures with extracellular enzyme production and persistence in processing environments (Quintieri et al., 2021).

Among these organisms, *P. fluorescens* has received particular attention. In raw-milk samples collected across different regions of China, it represented 75.8% of the *Pseudomonas* isolates, and 68.9% of those isolates displayed proteolytic activity at 4°C, indicating that some strains can contribute to deterioration even during refrigeration (Li et al., 2022). Spoilage potential is not uniform across the genus: Narvhus et al. (2021) documented marked differences between cold-stored isolates in their ability to break down proteins and fats, and similar strain-to-strain variation has been reported among raw-milk isolates more generally (Baur et al., 2015). Consequently, detecting *Pseudomonas* or measuring its total population does not by itself reveal how severe the resulting quality loss will be.

Evidence from India is consistent with this picture. In a survey of milk and fermented milk products from dairies in Nashik district, all 60 psychrotrophic isolates grew at 7°C and most produced extracellular proteases or lipases; the isolates included *P. putida*, *P. stutzeri*, and *B. cereus* (Patil, 2019). Such studies remain few, and the strain-level spoilage potential of psychrotrophs in Indian cattle and buffalo milk is poorly characterized.Pasteurization kills vegetative *Pseudomonas* cells, but it does not necessarily inactivate the extracellular proteases and lipases the bacteria have already released (Machado et al., 2017; de Oliveira et al., 2015). Proteases break casein and other milk proteins into smaller peptides and nitrogen-containing compounds, which may appear as bitterness, sediment, coagulation, altered viscosity, or reduced product stability. Li et al. (2022) and Zhang et al. (2020) reported substantial residual protease activity after treatments at pasteurization-level and higher temperatures. In other words, destroying the bacterial cells does not automatically remove the spoilage potential created before processing. Lipases act on milk triglycerides, releasing free fatty acids that can produce rancid, bitter, or soapy notes depending on their type and concentration; their activity varies with bacterial strain, incubation temperature, and storage time (Narvhus et al., 2021).

Pseudomonas can also attach to processing equipment and develop biofilms. These attached populations may persist in tanks, pipelines, valves, and other difficult-to-clean locations, making repeated contamination possible. In a study of a pasteurized-milk production line, Chang et al. (2024) recovered 106 *Pseudomonas* strains, of which more than half could produce proteases, lipases, and biofilm. The finding shows why the processing environment deserves attention alongside the quality of incoming raw milk. Post-pasteurization contamination by Gram-negative bacteria and spore-formers remains an important route to sensory defects and reduced shelf life (Su et al., 2025; Lau et al., 2021), and heat-resistant enzymes such as the *Pseudomonas* protease AprX can contribute to destabilization and spoilage in UHT milk (Almeida et al., 2026).

3.2 Gram-positive spore-forming bacteria

Unlike vegetative Gram-negative bacteria, some Gram-positive organisms survive processing as endospores. These structures are highly resistant to heat, drying, and other environmental stresses, allowing spore-formers to persist through conventional thermal treatments and creating a continuing challenge for dairy processors (Gopal et al., 2015).

3.2.1 Bacillus

Bacillus species are common environmental contaminants of milk and dairy products. Considerable variation between locations and product types indicates that contamination levels differ across the dairy chain (Sun et al., 2025). *B. cereus* is notable because it is relevant to both food safety and spoilage, while other species, including *B. licheniformis* and *B. subtilis*, can impair quality through the enzymes they produce.

B. licheniformis is considered an important spore-former at several points in dairy production, from raw milk and ingredients to finished products. Its spores withstand environmental stress, and some strains can form biofilms. The proteases and lipases produced by this species break down milk proteins and fats, contributing to off-flavours, changes in texture, and shorter shelf life, and some of these enzymes are relatively heat resistant (Dai et al., 2024).

3.2.2 Paenibacillus

Paenibacillus includes psychrotolerant spore-formers associated with refrigerated fluid milk. Their significance lies in the combination of spore formation and the capacity of certain species to grow at low temperatures. In their study of *P. odorifer*, Buehler et al. (2022) observed faster growth at 7°C than at 4°C, and showed that spore formation and heat resistance do not translate in a simple way into spoilage within a particular shelf-life period. Finding an organism associated with spoilage therefore does not mean that visible deterioration will occur in every batch; the outcome depends on the initial population, strain, storage temperature and duration, and enzyme-producing capacity.

3.3 Other groups with product-specific roles

3.3.1 Lactic acid bacteria

Lactic acid bacteria (LAB), such as *Lactococcus*, *Lactobacillus*, and *Leuconostoc*, cannot be classified as harmful in every dairy setting. They are essential starter organisms in many fermented foods, yet their uncontrolled growth in fluid milk causes unwanted souring. By converting lactose into organic acids, especially lactic acid, they lower the pH and destabilize casein micelles, eventually leading to coagulation. Their effect therefore depends on the product and the degree of control over fermentation: in yogurt and many cheeses, their growth is intentional and desirable. Researchers have also investigated selected LAB as protective cultures that may suppress spoilage organisms and pathogens (Girma, 2021; Shi & Maktabdar, 2022).

3.3.2 Enterobacteriaceae

Enterobacteriaceae such as *Enterobacter*, *Citrobacter*, and *Klebsiella* may enter milk through environmental exposure or inadequate hygiene (El-Mokadem et al., 2020). Their detection can indicate sanitation problems or possible faecal contamination. Some members ferment available carbohydrates, producing acids and gases that contribute to abnormal odours, souring, gas formation, and textural defects. Results should be interpreted alongside other microbiological findings and indicators of hygiene (Mladenović et al., 2021).

3.3.3 Clostridium

Clostridium species are anaerobic, spore-forming bacteria. Their spores may originate in soil or feed and reach milk through environmental contamination. Their effects are most evident in certain dairy products, particularly cheese, where clostridial fermentation under anaerobic conditions can release gas and undesirable metabolites (Oliveira et al., 2016). They are therefore more closely associated with defects in susceptible cheeses than with routine spoilage of refrigerated fluid milk.

3.3.4 Moulds and yeasts

Moulds and yeasts are relevant spoilage agents in a number of fermented dairy foods. *Penicillium*, *Aspergillus*, and *Mucor*, along with various spoilage yeasts, are often associated with butter and ripened cheese (Garnier et al., 2017). Fungi can tolerate the relatively low pH and water activity of cheese, and in yogurt and other cultured products their growth may lead to yeasty odours, bitter flavours, and gas production (Ledenbach & Marshall, 2009).

4. How Spoilage Shows Up: Mechanisms and Quality Defects

Microbial growth changes more than the bacterial count of milk. Through their metabolism and enzyme activity, microorganisms can alter its chemical composition, physical behaviour, sensory qualities, nutritional value, and suitability for further processing. Psychrotrophic *Pseudomonas* and spore-formers such as *Bacillus* and *Paenibacillus* are of particular concern because certain strains release extracellular proteases and lipases that remain active after heat treatment (Martin et al., 2021; Narvhus et al., 2021; Dai et al., 2024). Table 3 summarizes how these mechanisms map onto the organisms responsible, the milk components affected, and the resulting defects.

Table 3. Principal spoilage mechanisms and their consequences (Dai et al., 2024)

Spoilage mechanism	Main bacterial contributors	Milk component affected	Principal consequence
Proteolysis	*Pseudomonas*, *Bacillus*, *Paenibacillus*	Casein and whey proteins	Bitterness, sediment, gelation
Lipolysis	*Pseudomonas*, *Bacillus*	Milk triglycerides	Rancid or soapy flavour
Acidification	LAB, some Gram-negative bacteria	Lactose	Sourness and coagulation
Gas production	Enterobacteriaceae, *Clostridium*	Carbohydrates	Gas, swelling, texture defects
Biofilm formation	*Pseudomonas*, *Bacillus*, and others	Processing surfaces	Persistent, recurring contamination
Pigment or metabolite production	Selected bacterial strains	Various substrates	Discoloration and abnormal odour

4.1 Proteolysis: the breakdown of protein

Proteolysis is among the most consequential forms of milk deterioration. *Pseudomonas*, *Bacillus*, and *Paenibacillus* can release extracellular proteases that hydrolyse casein and whey proteins. As degradation progresses, milk may develop bitterness, sediment, coagulation, or gelation, while its physical stability and consumer acceptability decline (Zhang et al., 2020; Li et al., 2022). Because

some of these enzymes tolerate heat, pasteurization may destroy the bacteria without stopping the reactions that continue during storage.

4.2 Lipolysis: the breakdown of fat

Lipolysis occurs when microbial lipases act on milk fat, splitting triglycerides and releasing glycerol and free fatty acids. When particular fatty acids accumulate, they can give milk a rancid, bitter, or soapy taste. These flavour defects reduce acceptance and may also affect the quality of products manufactured from the milk (Narvhus et al., 2021).

4.3 Acidification and coagulation

Some bacteria, especially LAB, use lactose as a substrate and convert it into organic acids, including lactic acid. As acidity rises, the pH falls and casein micelles become less stable (Darwesh et al., 2025). Coagulation may follow, leaving the milk sour, thicker than normal, or visibly curdled.

4.4 Gas production

Gas may be produced when Enterobacteriaceae and *Clostridium* ferment carbohydrates. Excessive gas in milk and dairy foods can cause foaming, package swelling, unusual texture, and structural defects. This is particularly troublesome in fermented products and cheese, where gas-related problems may appear as early blowing, mechanical holes, off-odours, and off-flavours (Karanth et al., 2023).

4.5 Sensory and physical change

The acids, peptides, fatty acids, sulphur-containing compounds, and other metabolites generated by microbial activity shape the sensory character of deteriorating milk. Proteolysis is commonly associated with bitterness, fat breakdown with rancid or soapy notes, and acid production with sourness as pH declines (Narvhus et al., 2021). Some pigment-producing *Pseudomonas* lineages cause colour defects in dairy products worldwide (Reichler et al., 2019). Alongside these flavour, odour, and colour changes, enzyme activity and microbial metabolites can alter the physical appearance and structure of the product, resulting in:

- Increased viscosity
- Sediment formation
- Protein coagulation
- Gelation
- Separation of milk components
- Changes in appearance

These changes are especially important in refrigerated and extended-shelf-life milk, where buyers expect the product to retain a consistent appearance and texture throughout the stated storage period (Yalew et al., 2024). Table 4 brings together the main microbial colour, flavour, and body defects and the organisms associated with them.

Table 4. Microbial defects in milk, their causative organisms, and causes (Fusco et al., 2020)

#	Type	Defect	Organism(s)	Cause / description
1	Colour	**Blue milk**	*Pseudomonas syncyanea* (*P. cyanogenes*)	Blue pigment forms on the surface and spreads. Usually follows contamination from water or equipment.
2	Colour	**Yellow milk**	*Pseudomonas synxantha*, *Flavobacterium* spp.	Yellow pigment forms, often in cold-stored milk.
3	Colour	**Red milk**	*Serratia marcescens* (prodigiosin), *Micrococcus roseus*	Red patches or surface colour. *Serratia* can also cause bitterness and ropiness.
4	Colour	**Brown milk**	*Shewanella putrefaciens* (formerly *Pseudomonas putrefaciens*), some *Bacillus* spp.	Proteolysis with pigment formation, usually with a putrid odour.
5	Colour	**Orange or pink milk**	*Micrococcus*, *Rhodotorula* (yeast)	Pigmented surface growth.
6	Flavour	**Sour milk**	*Lactococcus lactis*, *Lactobacillus* spp.	Lactose is fermented to lactic acid, lowering pH. The commonest spoilage of raw milk.
7	Flavour	**Bitter milk**	*Bacillus subtilis*, *Pseudomonas*, *Proteus*, *Micrococcus*, *Serratia*	Proteolysis forms bitter peptides. Heat-stable proteases survive pasteurization.
8	Flavour	**Fruity flavour**	*Pseudomonas fragi*	Produces esters such as ethyl butyrate.

#	Type	Defect	Organism(s)	Cause / description
9	Flavour	**Malty or burnt flavour**	*Lactococcus lactis* var. *maltigenes*	Produces 3-methylbutanal and related compounds.
10	Flavour	**Putrid or fishy odour**	*Pseudomonas*, *Proteus*	Protein breakdown releases amines and sulphur compounds.
11	Flavour	**Rancid flavour**	*Pseudomonas fluorescens*, *Bacillus* spp., yeasts, moulds	Lipases release free fatty acids such as butyric acid.
12	Flavour	**Yeasty or alcoholic flavour**	*Kluyveromyces*, *Candida* (lactose-fermenting yeasts)	Fermentation produces alcohol and CO_2.
13	Flavour	**Unclean or barny flavour**	Coliforms and other contaminants	Poor hygiene or feed odours.
14	Body	**Ropy or slimy milk**	*Alcaligenes viscolactis*, *Klebsiella* (*Enterobacter*) *aerogenes*, some *Lactococcus* strains	Capsular polysaccharides make the milk viscous and stringy.
15	Body	**Sweet curdling**	*Bacillus cereus*, *B. subtilis*, *Micrococcus*	Rennet-like enzymes coagulate milk without a pH drop. The curd is often digested later.
16	Body	**Gassiness**	*E. coli*, *Enterobacter*, *Clostridium* spp., yeasts	Gas (CO_2, H_2) from fermentation. In cheese, coliforms cause early blowing and *C. tyrobutyricum* causes late blowing.
17	Body	**Stormy fermentation**	*Clostridium perfringens*	Vigorous gas production tears the curd apart.
18	Body	**Proteolysis or peptonization**	*Bacillus*, *Pseudomonas*, *Proteus*	Casein is digested, leaving the milk clear and translucent.
19	Body	**Thin or watery appearance**	Proteolytic bacteria	A result of protein breakdown.

4.6 Differences between products

The pattern and speed of deterioration are not identical across dairy products. Spoilage patterns differ between skim and whole milk (Deeth et al., 2002). Cheese can be affected by both Gram-positive and Gram-negative bacteria, with possible outcomes including early blowing, off-odours, excess moisture or dryness, and mechanical holes (Karanth et al., 2023). In yogurt and other cultured foods, fungal growth may instead be noticed through yeasty smells, bitterness, or gas. Equipment surfaces add a risk that cuts across products: *Bacillus* spores are highly hydrophobic and can attach strongly to inert surfaces, including stainless steel, which encourages the formation of persistent biofilm reservoirs that may repeatedly contaminate production equipment (Wiencek et al., 1990; Husmark & Rönner, 1992). Once contamination becomes established in raw milk or on equipment, an entire batch may be put at risk (Marchand et al., 2012).

4.7 Nutritional and technological consequences

When microbial activity substantially degrades proteins, fats, or carbohydrates, the nutritional and functional properties of milk may also be affected. Proteolysis and lipolysis can interfere with processing performance, reducing the suitability of the raw material for cheese manufacture, milk-powder production, and other dairy applications.

4.8 Shortened shelf life

Taken together, bacterial multiplication and the action of microbial enzymes reduce the period for which milk remains usable. Chilling slows growth but does not stop psychrotrophic bacteria. During extended cold storage, *Pseudomonas* may therefore become dominant and produce spoilage enzymes before the product reaches the end of its labelled shelf life (Martin et al., 2021; Yalew et al., 2024).

5. Temperature: The Decisive Lever

Storage temperature strongly shapes the rate at which bacteria develop in milk and can be managed at every stage from milking to retail. Refrigeration is indispensable, but it slows rather than stops the growth of cold-tolerant psychrotrophs, and prolonged cold storage favours those that produce heat-stable proteases and lipases (Zhang et al., 2020). Differences within the refrigeration range

are consequential: *Paenibacillus odorifer* grew faster at 7°C than at 4°C (Buehler et al., 2022), and all 60 psychrotrophic isolates in an Indian dairy survey grew at 7°C (Patil, 2019). Storage conditions can also outweigh processing conditions. Lott et al. (2023) found that storage temperature had a much greater effect on the growth of spore-forming bacteria in fluid milk than relatively small changes in high-temperature, short-time (HTST) pasteurization temperature, and that even a modest rise in storage temperature can markedly reduce the time milk remains saleable. Temperature must therefore be managed during transport, storage, and retail handling, and not treated as a responsibility limited to the processing facility. The implication is sharper still in warm climates such as much of India, where high ambient temperatures can erode the benefit of the cold chain at every handover.

6. The Cost of Spoilage: Economic and Environmental Impacts

The effects of spoilage are not confined to the milk that is ultimately thrown away. Deterioration can weaken consumer confidence in dairy quality and reliability, while creating broader challenges for food security, nutrition, and environmental sustainability (Martin et al., 2021). Effective control of spoilage organisms is consequently important not only for product quality and safety, but also for preserving shelf life and the value of dairy production.

6.1 Global scale of losses

The financial scale of milk spoilage is substantial. Worldwide losses have been estimated at approximately USD 5–6 billion annually (Lu & Wang, 2017). In the United States, around one-quarter of dairy products are lost during production or wasted at retail and consumer level each year (Griffin et al., 2009). In 2010, dairy accounted for roughly 17% of the value of food lost or wasted at retail and consumer level, making it the third-largest category after meat, poultry, and fish (30%) and vegetables (19%) (Buzby et al., 2014). Microbial growth, particularly by psychrotrophic bacteria, has been implicated in approximately 50–60% of fluid-milk spoilage in the United States (Martin et al., 2018). Enzymatic damage can also be disproportionate to cell numbers: populations as low as about 1.3×10^5 CFU/mL can produce heat-resistant proteases and lipases in raw milk before processing (Machado et al., 2017), and these enzymes may later cause technological problems, including lower cheese yield, undesirable flavours, and gelation.

6.2 Where along the chain losses occur

The costs of spoilage fall unevenly along the chain. Six categories can be distinguished:

- **Raw-milk rejection.** When a milk consignment does not meet microbiological standards, a processor may refuse it. The farmer then loses the expected income despite having already paid for feed, labour, water, housing, and milking (Chambers, 2005). The impact can be particularly severe for small producers, for whom one rejected collection may represent a sizeable portion of the day's earnings.
- **Reduced shelf life.** If milk deteriorates earlier than expected, fewer days remain for transport, distribution, and sale. This is a particular concern for refrigerated fluid milk because psychrotrophic organisms may compromise quality before the printed expiry or best-before date (Yalew et al., 2024; Wang et al., 2026).
- **Product disposal.** Milk that develops unacceptable sensory or physical defects may have to be withdrawn from sale. The financial loss exceeds the value of the milk itself because packaging, processing, refrigeration, transport, and labour have already added cost (Martin et al., 2021).
- **Processing losses.** Enzymes produced by spoilage organisms can damage milk intended for further manufacture. The breakdown of proteins and fats may reduce raw-material suitability, lower yield, or compromise the quality of the finished product (Ntuli et al., 2023), so the consequences extend beyond retail milk that visibly spoils.
- **Sanitation costs.** Persistent contamination creates a need for more frequent cleaning, sanitation, environmental sampling, and investigation. Biofilm-forming and spore-forming organisms are particularly troublesome because they may reappear even after cleaning appears to have been successful (Dai et al., 2024; Santos et al., 2025).
- **Laboratory and monitoring costs.** Repeated spoilage events call for additional microbiological testing and environmental monitoring to locate the source of contamination. Rapid molecular methods may help limit some of this expense by identifying warning signs earlier (Wang et al., 2026).

Table 5 maps these losses to the stage of the supply chain at which they arise.

Table 5. Spoilage-related losses by stage of the supply chain (Karanth et al., 2023)

Stage	Spoilage-related problem	Direct economic consequence	Indirect consequence
Farm	High bacterial load	Milk rejection or reduced payment	Loss of producer income
Collection	Prolonged storage	Increased microbial growth	Reduced raw-material value
Processing	Enzymatic deterioration	Processing and product losses	Lower product quality
Processing plant	Biofilm or spore contamination	Extra sanitation	Production interruption

Stage	Spoilage-related problem	Direct economic consequence	Indirect consequence
Packaging	Post-processing contamination	Product rejection	Reduced consumer confidence
Distribution	Temperature abuse	Shortened shelf life	Increased unsold inventory
Retail	Premature spoilage	Product disposal	Food waste
Quality control	Recurrent contamination	More testing	Higher monitoring costs

6.3 Economic losses from milk spoilage in India

Estimates of the economic cost of spoilage specific to India are scarce, and no study isolates microbial spoilage from other causes of loss. What can be assembled are measurements of overall post-harvest milk loss, which include spoilage, together with data on the size of the sector.

Value of the sector. Applying milk's 65.9% share of livestock output to the ₹9.19 lakh crore gross value of livestock output in 2023–24 (MoSPI, 2025) gives a value of about ₹6.1 lakh crore for milk.

Measured post-harvest losses. The national assessment by the Indian Council of Agricultural Research–Central Institute of Post-Harvest Engineering and Technology (ICAR-CIPHET) put harvest and post-harvest loss of milk at 0.92% (Jha et al., 2015). The more recent study by NABARD Consultancy Services (NABCONS), with a reference period of 2020–22, reported state-level losses ranging from 0.50% in Gujarat to 1.35% in Rajasthan (NABCONS, 2022; Table 6). Losses were below 0.8% in Gujarat, Madhya Pradesh, Andhra Pradesh, Punjab, Maharashtra, and Haryana, and above 1% in Uttar Pradesh, Telangana, Uttarakhand, and Rajasthan.

Table 6. Reported post-harvest milk losses in India

Study	Coverage	Milk loss (% of production)
ICAR-CIPHET (2015)	India (national)	0.92
NABCONS (2022)	Gujarat	0.50
NABCONS (2022)	Madhya Pradesh	0.53
NABCONS (2022)	Andhra Pradesh	0.58
NABCONS (2022)	Punjab	0.63
NABCONS (2022)	Maharashtra	0.65
NABCONS (2022)	Haryana	0.74
NABCONS (2022)	Uttar Pradesh	1.09
NABCONS (2022)	Telangana	1.12
NABCONS (2022)	Uttarakhand	1.16
NABCONS (2022)	Rajasthan	1.35

Sources: Jha et al. (2015); NABCONS (2022), as reported in a Government of India parliamentary reply. NABCONS state-level data were available for the ten states shown.

Indicative monetary value. Applying these loss percentages to 2023–24 production (239.30 million tonnes; DAHD, 2025) and to the approximate value of milk output gives the indicative range in Table 7: roughly 1.2–3.2 million tonnes of milk, worth about ₹3,000–8,200 crore a year, with a central estimate of about ₹5,600 crore. These values describe all causes of post-harvest loss, not microbial spoilage alone.

Table 7. Indicative annual value of milk lost after harvest in India

Scenario	Loss rate applied	Loss (%)	Milk lost (million tonnes)	Indicative value (₹ crore)

Scenario	Loss rate applied	Loss (%)	Milk lost (million tonnes)	Indicative value (₹ crore)
Low	Lowest state value (Gujarat)	0.50	1.20	≈ 3,000
Central	National estimate (ICAR-CIPHET)	0.92	2.20	≈ 5,600
High	Highest state value (Rajasthan)	1.35	3.23	≈ 8,200

Calculated as loss rate × 239.30 million tonnes (2023–24 production) and loss rate × ₹6.06 lakh crore (approximate 2023–24 value of milk output). These are order-of-magnitude values, not measured estimates.

These figures probably underestimate the true economic cost of spoilage, for four reasons. First, physical-loss surveys count milk that is discarded but not milk that is sold at a discount, downgraded, rejected by one buyer and resold to another, or diverted to lower-value use after souring; the monetary cost of such milk can be considerable even though little is physically lost. Second, with about 68% of marketable milk handled by the unorganised sector (Pashu Sandesh, 2026), sampling-based loss estimates are likely to capture informal channels less completely than organised ones. Third, the 2018 FSSAI survey reported that 39% of samples failed one or more quality parameters but, because it did not include microbiological tests, it cannot reveal how much of that milk was microbially compromised (FSSAI, 2018). Fourth, losses at the retail and household levels are not captured by the farm- and market-level estimates in Table 6.

Mastitis and raw-milk quality. Mastitis is a production disease rather than a spoilage process, but it shapes the quality of raw milk entering the chain and carries large costs of its own. A systematic review and meta-analysis estimated the pooled prevalence of subclinical and clinical mastitis in Indian dairy animals at about 45% and 18%, respectively (Krishnamoorthy et al., 2021), and the combined annual economic loss has been estimated at about ₹7,165 crore (Bansal & Gupta, 2009). These losses arise mainly from reduced yield, discarded milk, treatment, and culling.

6.4 Food waste and the environment

The environmental cost of discarded milk accompanies its financial cost. When a batch is wasted, the resources used to produce and deliver it are wasted as well: animal feed, agricultural land, water, energy, packaging, transport, and refrigeration (Ghosh et al., 2016). Snyder et al. (2024) identify microbial spoilage as an important contributor to food waste and its environmental burden. This burden is often expressed as carbon-dioxide-equivalent emissions, which compare the warming impact of greenhouse gases with that of CO_2 (Brander, 2012). Estimates indicate that global fluid-milk production, processing, and transport generate about 2.4 kg CO_2-equivalent per kilogram of milk and account for approximately 2.7% of global anthropogenic greenhouse-gas emissions (FAO, 2010; Gerber et al., 2013). Each litre lost to spoilage therefore represents avoidable expenditure and an unnecessary environmental impact.

7. Stopping Spoilage: An Integrated, Chain-Wide Strategy

Because contamination can enter at every stage, control must also operate at every stage. The measures below follow the chain from the farm to the point of sale and then turn to priorities specific to India.

7.1 Hygienic milk production

Effective prevention begins before milk leaves the farm. Clean udders, hygienic milking practices, properly maintained equipment, microbiologically suitable water, and appropriate storage of feed and bedding all help limit the initial contamination load. This first level of control matters because refrigeration cannot indefinitely make up for poor-quality raw milk.

7.2 Rapid cooling and temperature control

Cooling milk soon after milking slows the growth of many mesophilic bacteria, but it should be understood as a means of controlling growth rather than eliminating psychrotrophs. Low temperatures need to be maintained consistently during collection, transport, storage, and distribution. As noted in Section 5, Lott et al. (2023) showed that even a moderate increase in storage temperature can accelerate bacterial growth.

7.3 Cleaning, sanitation, and spore control

Cleaning programmes need to remove milk residues while also preventing microorganisms from establishing persistent biofilms. Particular care is required around joints, valves, and other locations that are difficult to access. Spores are especially challenging once they have become established, so preventing their entry is a priority. Reducing soil, feed, and bedding contamination at farm level can help lower the number of spores entering milk. Recent work has shown that aerobic spore-formers may survive pasteurization and contribute to early spoilage in pasteurized milk, reinforcing the importance of both raw-milk quality and hygiene within the plant (Santos et al., 2025).

7.4 Thermal processing

UHT treatment exposes milk to approximately 135–142°C for a few seconds, followed by aseptic packaging. This sharply reduces the microbial load and can extend shelf life for months without refrigeration, although the process is not used for every dairy product (Rauh & Xiao, 2022; Kelly et al., 2022). However, heat treatment cannot be relied upon to reverse enzyme activity that began before processing. Good-quality raw milk and hygienic handling therefore remain necessary, even when intensive thermal processing is used.

7.5 Rapid detection

Traditional culture-based microbiological tests remain valuable, although they may take time to produce results. Molecular and other rapid approaches could provide earlier indications of high-risk microbial populations and improve decisions about quality and shelf-life management (Yalew et al., 2024; Wang et al., 2026). Potential indicators of spoilage include carbon dioxide concentration, bacterial counts, and shifts in pH, and emerging tools, including smartphone-based vibration sensing, are being developed to identify microbial deterioration without opening the package or sampling the milk (Cranz et al., 2020; Wu et al., 2024; Lu et al., 2013).

7.6 Priorities for the Indian dairy chain

Several priorities are particularly relevant to the Indian dairy chain.

- **Chilling close to the point of production.** Because the interval between milking and cooling is where psychrotrophic and mesophilic growth is least controlled, extending cooling capacity to village collection points would address the stage at which smallholder milk is most exposed.
- **Bringing informal channels under quality control.** With about two-thirds of marketable milk outside the organised sector, hygiene training, access to cleaning and cooling facilities, and incentives linked to quality are likely to yield larger gains than further tightening of controls in plants that already operate cold chains.
- **Udder health and clean milk production.** The high prevalence of mastitis in Indian herds raises the microbial and residue burden of raw milk and the cost of production, so control of mastitis serves both quality and economic objectives.
- **Microbiological surveillance.** National quality surveys have so far concentrated on composition, adulterants, and chemical contaminants (FSSAI, 2018). Adding microbiological indicators, including psychrotroph and spore counts, would show where spoilage risk is concentrated.
- **Quality-based payment and rapid tests.** Simple, low-cost tests at collection points, combined with payment that rewards low bacterial counts, would give producers a direct financial reason to improve hygiene and cooling.

8. Knowledge Gaps and Future Directions

Several gaps limit both the understanding of spoilage and the design of effective interventions.

- **Bacterial counts alone are not enough.** Samples with similar total counts can show very different levels of deterioration because individual strains differ in their proteolytic, lipolytic, and biofilm-forming capacities (Narvhus et al., 2021).
- **Greater attention to strain-level traits.** Within *Pseudomonas*, differences between species and strains influence both the quantity and stability of spoilage enzymes. These differences need to be better characterized.
- **Connecting farm contamination with finished-product quality.** More work is needed to clarify how organisms entering with raw milk relate to those introduced or amplified during processing, and how each source contributes to spoilage in the final product.
- **A clearer economic breakdown.** Future studies should distinguish the costs associated with milk rejection, reduced shelf life, processing inefficiency, product disposal, sanitation, laboratory testing, and transport.
- **Spoilage-specific data from India.** Existing Indian loss estimates combine all causes of post-harvest loss, and national quality surveys have not included microbiological testing. Studies that quantify microbial spoilage separately, in organised and unorganised channels and in different seasons, are needed to turn indicative estimates into reliable ones. Most of the spoilage literature also derives from temperate, bovine, cold-chain systems, so the behaviour of spoilage organisms in tropical conditions and in buffalo milk deserves specific study.
- **Making rapid detection practical.** Genomic and molecular tools need to be incorporated into routine quality-management systems so that processors can identify spoilage-associated populations before sensory or visible defects develop.
- **Exploring non-thermal and biological controls.** Bacteriophages, naturally derived antimicrobials, protective cultures, and improved hurdle technologies may help reduce reliance on increasingly intensive processing. Their practical value deserves further investigation.

9. Conclusion

Bacterial activity remains one of the main limits on milk quality and commercial shelf life. Contamination can begin on the farm and continue through collection, chilling, transport, processing, and distribution. Among the organisms involved, psychrotrophic *Pseudomonas* spp. are especially important: they can multiply during refrigerated storage and release proteases and lipases that cause substantial deterioration. *Bacillus* and *Paenibacillus* present a different challenge because their spores can persist in dairy environments and contribute to spoilage after processing. Other groups, including lactic acid bacteria, Enterobacteriaceae, *Clostridium* spp., and spoilage fungi, play additional roles that vary across fluid milk, cheese, yogurt, and butter.The main routes of deterioration are protein breakdown, fat breakdown, acid production, gas formation, and biofilm-associated contamination. These processes lead to bitterness, rancidity, sourness, coagulation, gelation, sediment, and other quality defects. Their economic consequences include rejected raw milk, reduced shelf life, discarded products, processing difficulties, and higher expenditure on sanitation and testing. The global cost has been estimated at USD 5–6 billion annually, and dairy losses also carry an environmental burden because the resources and emissions associated with producing, processing, and distributing milk are wasted when the product is discarded.In India, the world's largest milk producer, these problems are magnified by a dispersed production base, a large unorganised sector, and a warm climate. Reported post-harvest losses of 0.5–1.4% of production correspond to an indicative ₹3,000–8,000 crore a year, and the true cost of spoilage, including downgrading and unrecorded losses in informal channels, is probably higher. Closing the evidence gap with microbiological surveillance and spoilage-specific loss accounting is a prerequisite

for targeting investment effectively.A reliable response must combine preventive measures across the dairy chain. Farm hygiene, prompt cooling, continuous temperature control, effective cleaning and sanitation, control of spore contamination, suitable heat treatment, and timely microbial detection all have a role. Future research would benefit from closer attention to strain-specific spoilage potential and from more precise estimates of the economic contribution of individual deterioration pathways. Such evidence could support more targeted interventions, helping the dairy sector reduce waste, protect product quality, extend shelf life, and limit both financial and environmental losses.

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