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Cleaning of milk storage tanks: A review

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Abstract

Cleaning of milk containers is of paramount importance to the quality and safety of milk during its storage, gathering and transit. This review provides an overview of the methods and practices used for cleaning of milk storage tanks, emphasizing their significance to dairy processing and hygiene, and consumer safety. Focusing on effectiveness of preventing contamination, microbial growth and maintaining the integrity of the product, this paper reviews various methods and practices used for cleaning of milk storage tanks. The paper surveys more recent authentication methods, which include automatic cleaning systems and application of antimicrobial coatings, along with traditional cleaning methods, i.e., hand washing and use of detergents. Key factors influencing the efficacy of cleaning, the nature of the cleaning agents, temperature and the composition of the storage vessel material, are emphasized in the review. These factors are thoroughly evaluated to better understand their influence on cleaning efficiency. Further issues relating to protracting organic wastes and bacterial biofilm formation are treated; as are current advances in the field of cleaning. In addition to the most recent advances in practices and equipment for cleaning, common issues such as persistence of organic residues, and bacterial biofilm formation are also covered. The challenges and complexity of a number of cleaning methods are also addressed. The review also highlights the existing research gaps and sustainability aspects related to dairy sanitation processes. It combines current knowledge with recent technological advances and therefore can be a valuable source of information for researchers and professionals in the dairy industry interested in improving cleaning efficiency, product safety, and sustainable dairy processing practices. Lastly, suggestions for improving cleaning methods in dairy companies stress the need of constant research and innovation in this field to guarantee both product safety and sustainability.

Keywords: Milk container cleaning, dairy sanitation, microbial contamination, biofilm control, dairy processing hygiene

Introduction

Food is the basic requirement for all living organisms, as it provides the necessary nutrients for life. As per Food and Agriculture Organisation (2024) India is one of the largest producers of food in world and occupies second position after China. India is ranked first in milk production contributing 24.76% of global milk production (BAHS, 2025). Milk production is growing at Compound Annual Growth Rate (CAGR) of 5.62% over the past 10 years from 146.31 million tonnes during 2014-15 to 247 million tonnes during 2024-25 with a *per capita* availability of 485g/day (BAHS, 2025) [30, 29].

Milk is one of the most important food commodities in the world. More than 6 billion people worldwide of all ages consume milk and milk products as it is a good source of vitamins and minerals which are vital for life (FAO, 2024) [28] [28]. It is a highly perishable product due to its high moisture content (80-87%) and nutrients, if it's not handled well it may lead to huge losses [30].

As India lies in the Torrid Zone, losses of milk due to spoilage is high, in summer season the farmers can lose as much as 30% of their milk to spoilage. About 55MT were lost before they even reach the stores due to delay in

production, distribution and spoilage. The handling losses of milk during storage and transportation is very high in developing countries when compared with developed country (Gross, 2018) [7]. Therefore, maintaining hygiene could be a tool to increase the safety, shelf-life and bioavailability of nutrients.

Cleaning is the paramount process in dairy industry. It is the removal of deposit layers from the process equipment and an essential operation for many industrial processes subject to fouling. Pant *et al.*, (2023) [19] [19] stated that cleaning is the series of operation aiming at removal of dirt from equipment surface areas through the use of detergents or mechanical means. According to the Food standard code, effective "cleaning" defined as the removal of general dirt, grease and food waste [7, 20].

Storage tank cleaning is a critical maintenance process required to ensure the safe, efficient, and hygienic operation, including those used in industrial, agricultural, and commercial settings (Lelieveld *et al.*, 2016; Codex Alimentarius Commission, 2020) [31] [30]. Whether it's a storage tank, transport tank, or a containment vessel regular cleaning is essential to prevent contamination, avoid safety hazards, and extend the life of the equipment.

The process typically involves the removal of residues, sludge, or harmful build-ups inside the tank. This can be done through mechanical, chemical, or manual methods, depending on the tank's contents and purpose. Cleaning plays a pivotal role in industries such as food and beverage production, oil and gas, pharmaceuticals, and wastewater treatment, where the integrity of stored materials and the maintenance of hygiene standards are of utmost importance. In addition to maintaining safety and cleanliness, proper cleaning also helps to optimize operational efficiency, minimize downtime, and reduce the risk of costly repairs or environmental issues ^[29].

Present status of cleaning in Dairy Industry

Cleaning and sanitation are fundamental operations in the dairy and food industries, playing a critical role in ensuring product quality, consumer safety, and regulatory compliance (Pant *et al.*, 2023) ^[19]. The increasing demand for high-quality food products, coupled with stringent food safety regulations, has driven significant advancements in cleaning technologies and sanitation practices over the past decades (Jovanović *et al.*, 2026) ^[32].

Cleaning-in-Place (CIP) systems have become the predominant cleaning method in dairy processing plants because they enable the cleaning of pipelines, storage tanks, pasteurizers, and other processing equipment without disassembly (Van Asselt *et al.*, 2025) ^[26] ^[26]. Conventional CIP procedures typically involve pre-rinsing, alkaline cleaning, acid cleaning, intermediate rinsing, and sanitization steps to remove organic residues, mineral deposits, and microbial contaminants from food-contact surfaces (Pant *et al.*, 2023) ^[19] ^[19]. These systems have improved process efficiency and hygiene control; however, they remain associated with high water, energy, and chemical consumption (Van Asselt *et al.*, 2025).

Recent research has focused on enhancing the sustainability and effectiveness of cleaning operations. Enzyme-based cleaning agents have emerged as promising alternatives to conventional detergents because they can effectively degrade proteinaceous and fatty deposits while reducing cleaning temperatures and chemical usage (Pant *et al.*, 2023) ^[19]. Similarly, novel technologies such as plasma-activated water, cold plasma treatments, and ozone-based cleaning systems have demonstrated potential for improving cleaning efficiency and microbial inactivation while minimizing environmental impacts (Shah *et al.*, 2024; de Souza *et al.*, 2024) ^[5, 22, 5, 22].

Biofilm formation remains one of the major challenges in dairy and food processing environments. Foodborne pathogens and spoilage microorganisms can adhere to equipment surfaces and develop biofilms that are resistant to conventional cleaning and sanitizing procedures (EFSA BIOHAZ Panel, 2024) ^[6]. Consequently, considerable attention has been directed toward the development of advanced sanitation strategies, antimicrobial surface coatings, and improved cleaning validation methods to ensure effective biofilm removal (Mancinelli *et al.*, 2024) ^[15].

Hygienic equipment design has also gained increasing importance in modern food processing facilities. International organizations such as the European Hygienic Engineering and Design Group (EHEDG) and 3-A Sanitary

Standards advocate equipment designs that minimize crevices, dead zones, and inaccessible surfaces where residues and microorganisms may accumulate (Jovanović *et al.*, 2026) ^[32]. The adoption of hygienic design principles has significantly improved cleanability and reduced contamination risks in food processing operations.

The integration of digital technologies and automation represents another emerging trend in industrial cleaning. Real-time monitoring systems, sensors, data analytics, and artificial intelligence are increasingly being employed to optimize cleaning cycles, monitor process parameters, and verify cleaning effectiveness (Food Engineering Magazine, 2025). These technologies facilitate resource-efficient cleaning operations while supporting predictive maintenance and process control.

Verification and validation of cleaning procedures have become increasingly sophisticated. Traditional methods such as visual inspection and microbiological testing are now complemented by ATP bioluminescence assays, surface residue analysis, conductivity measurements, and automated monitoring systems to assess cleaning performance and ensure compliance with food safety standards (Guerrero & Ríos Duarte, 2024) ^[8].

In recent years, sustainability has become a key consideration in cleaning and sanitation practices. Research efforts are focused on reducing water consumption, minimizing chemical usage, improving energy efficiency, and developing environmentally friendly cleaning agents without compromising hygiene standards (Van Asselt *et al.*, 2025) ^[26]. Approaches such as dry cleaning, fogging technologies, enzyme-assisted cleaning, and water recycling systems are increasingly being explored to address these objectives (Mancinelli *et al.*, 2024; Sant'Ana *et al.*, 2025) ^[40] ^[15].

Overall, the current status of cleaning in the dairy and food industries is characterized by the widespread adoption of CIP systems, increasing implementation of hygienic design principles, advancements in cleaning validation techniques, and the emergence of sustainable and automated cleaning technologies. Despite these developments, challenges related to biofilm control, resource consumption, cleaning verification, and the removal of persistent residues continue to drive research and innovation in this field (EFSA BIOHAZ Panel, 2024; Van Asselt *et al.*, 2025) ^[6, 26, 31-33, 27, 5, 23, 6, 16, 8].

The Process of cleaning

The process of cleaning, whether it may be of manual or automated, tend to follow ilar patterns and usually consist of chain of distinct steps which run for a fixed time period. To attain the required level of cleanliness cleaning should be performed very strictly according to a carefully worked out procedure (Pant *et al.*, 2023) ^[19]. The cleaning cycle in dairy comprises of following steps ^[20]:

Recovery of Product Residues

In cleaning process, the product recovery refers to removal of any product remnants from the production line or tanks by means of by scraping, drainage or forcing out with water, compressed air, or mechanical pigging device. At the end of the processing, all the product residues should be recovered from the line as it helps in reduction of the load on the

sewage system and also it reduces the product loses and facilitates cleaning. In order to avoid filling of product recovery tank by pre-rinse water, more sophisticated methods have been developed by the dairy plants such as turbidity or conductivity sensors which help in differentiating the product and water (Tamime 2008 Tetra Pak, 2025) ^[39, 25, 26].

Pre-Rinsing

Pre-rinsing done with water in order to remove the loosely adhered solids from the surface of the equipment. It should always be carried out as soon as the production ends, if it delayed, the milk residues dry and get stick to the surfaces making the cleaning process difficult. The water used for the pre-rinse should be warm so that the fat is flushed out easily and if the temperature is higher than 60°C it may coagulate the protein which decreases the efficiency (Ahmad, 2009) ^[33]. The pre-rinse cycle for tanks, silos or vessels consists of several 'burst' or 'pulsed' rinses, as this both improves rinsing efficiency and can reduce water consumption significantly (Tamime, 2008, Pant *et al.*, 2023) ^[25, 19]. To avoid increase in detergent consumption, prerinsing should be continued until the rinse water leaving the equipment is clear, this will reduce the milk residues in the system and enhances the efficiency of cleaning (Ahmad, 2009) ^[41, 26, 34].

Detergent circulation

In order to obtain the required cleaning efficiency with the available detergent solution, the concentration, temperature, mechanical effect on the surfaces and the duration of cleaning cycle must be carefully monitored (Ahmad, 2009) ^[33] ^[33]. The product being processed and the processing system determine the temperature, concentration level, flow rate, and period of time that fluids are applied during a cleaning cycle. (Fryer, 2005, Pant *et al.*, 2023) ^[19, 34]. The concentration of the detergent solution in the process should be maintained because the solution gets neutralized during the process due to the rinsing water and milk residues. (Liu *et al.*, 2006) ^[13, 35, 14].

Post rinsing

Clean potable water is used for the post rinse. After the detergent cleaning, to remove the traces of the detergent from the system the water is circulated in the system. Because any traces of detergent can contaminate the product, softened potable cold water is used for flushing this reduces the formation of lime scales on the equipment surfaces. All the parts of the system should be thoroughly drained before disinfection of the system (Ahmad, 2009) ^[33, 32].

Disinfection: Cleaning with the acid and alkali detergent solution renders the system chemically, physically and bacteriologically safe, to further improve the bacteriological safety of the system it is disinfected with the oxidising biocide, such as sodium hypochlorite or peracetic acid solution (equilibrium mixture of acetic acid and hydrogen peroxide). Some non-oxidising biocides are also available, but they must be low foaming and fast acting in cold water in order to be effective for Cleaning. Disinfection with the hot water can also be done instead of chemical methods but

the input of thermal energy for the production of the hot water increases the cost of cleaning (Tamime, 2008) ^[25, 26].

Importance of cleaning: Cleaning is a fundamental operation in the dairy and food industries because it directly influences product quality, food safety, equipment performance, and consumer health. Effective cleaning removes food residues, microorganisms, and other contaminants from processing surfaces, thereby minimizing the risk of product spoilage and cross-contamination (Chowdhury *et al.*, 2025; Carrascosa *et al.*, 2021) ^[4, 3]. Biofilms and residual soils that remain on food-contact surfaces can serve as reservoirs for pathogenic and spoilage microorganisms, leading to contamination of subsequent production batches and reduced shelf life of food products (Carrascosa *et al.*, 2021; Jamal *et al.*, 2013) ^[41].

In the dairy industry, inadequate cleaning of milk handling and processing equipment can result in the accumulation of milk proteins, fats, and mineral deposits, which promote microbial growth and biofilm formation. These biofilms can harbor spoilage organisms and foodborne pathogens that adversely affect product quality and safety (Mogha *et al.*, 2014; Chowdhury *et al.*, 2025) ^[18, 4].

Cleaning is also essential for preventing foodborne illnesses. Pathogenic microorganisms such as *Listeria monocytogenes*, *Salmonella spp.*, *Escherichia coli*, and *Staphylococcus aureus* can persist on inadequately cleaned surfaces and contaminate food products during processing (Carrascosa *et al.*, 2021; Shi and Zhu, 2013) ^[3, 23]. Effective cleaning and sanitation programs therefore constitute a critical component of food safety management systems and Hazard Analysis and Critical Control Point (HACCP) programs.

Apart from ensuring microbiological safety, cleaning contributes to maintaining processing efficiency and equipment longevity. The accumulation of fouling materials on heat exchangers, storage tanks, and pipelines can reduce heat transfer efficiency, increase energy consumption, accelerate corrosion, and shorten equipment service life (Chowdhury *et al.*, 2025) ^[4]. Regular and effective cleaning helps maintain optimal equipment performance while reducing operational and maintenance costs.

Cleaning also plays a significant role in regulatory compliance and quality assurance. National and international food safety regulations require food processors to implement validated cleaning and sanitation procedures to ensure hygienic production conditions and protect consumer health (Chowdhury *et al.*, 2025) ^[4]. Failure to maintain adequate cleaning standards may result in product recalls, economic losses, reputational damage, and legal consequences for food manufacturers.

With increasing emphasis on sustainability, modern cleaning practices are additionally aimed at reducing water consumption, chemical usage, and energy requirements while maintaining high levels of hygiene. Advanced cleaning technologies, automated Cleaning-in-Place (CIP) systems, enzymatic cleaners, and smart monitoring systems are increasingly being adopted to improve cleaning efficiency and environmental performance (Chowdhury *et al.*, 2025) ^[4, 42, 3].

Overall, effective cleaning is indispensable in the dairy and food industries because it ensures food safety, prevents

microbial contamination, enhances product quality, improves equipment performance, supports regulatory compliance, and contributes to sustainable food processing operations (Chowdhury *et al.*, 2025; Carrascosa *et al.*, 2021) [4, 3].

Methods of cleaning

Effective cleaning is essential in dairy and food processing operations to remove product residues, prevent microbial contamination, maintain product quality, and ensure regulatory compliance. The selection of a cleaning method depends on equipment design, the nature of the soil, production scale, and hygienic requirements (Pant *et al.*, 2023) [19].

Manual cleaning

Manual cleaning using cloths, mops, brushes, pads, etc. It is normally used in small areas, equipment that is non-water proof or requires dismantling or areas which are difficult to clean by other methods. It is a labor-intensive method and may limit the use of certain chemicals for safety reasons. To ensure cleaning is effective the method must be clearly defined and staff trained to an appropriate level (Miller, 2022) [35].

Foam cleaning

Foam cleaning is a process that uses a foaming agent to clean surfaces. The foam works to loosen and lift dirt and debris from the surface, making it easier to remove. This type of cleaning is often used in factories and other industrial settings where there is a lot of dirt and greasy build-up. Foam cleaners can be used for internal and external cleaning of tanks, as well as floors, cladding, walls, production equipment and many other hard surfaces. Foam cleaning is often considered the best way to clean surfaces because the thick, clinging foam penetrates deep into crack, crevices and inaccessible areas to remove dirt, fat and debris, while the detergents dissolve greasy residue (Carrascosa *et al.*, 2021) [3].

Hydro blasting

Hydro blasting or water blast cleaning can effectively remove a wide variety of tough dirt in difficult-to-reach points or locations in a safe and efficient manner. In fact, the results are comparable to those of cleaning techniques that use abrasives and cleaning agents, but without the dust and other health hazards, which allows the workers to focus on their daily tasks in a health-friendly workplace environment. Water blasting operations are commonly categorized as high-pressure and ultra-high-pressure hydro blasting based on the following operating pressures: High-pressure water blasting - pressures from 690 bar (10,000 psi) to 1,700 bar (25,000 psi), Ultra-high-pressure water blasting - pressures of more than 1,700 bar (25,000 psi).

Machine Washing

This is normally an automatic or semi-automatic washing process conducted within a purpose-built machine. There are many machine designs depending on the application, e.g. crate washing or utensil washing. They represent a significant capital investment and need to have a clear business case before purchasing. They tend to consume a

large amount of chemicals and water. Failure to maintain them correctly can lead to a contamination risk to the product. Chemicals used in these machines should be low foaming. An effective system for controlling the dose of chemical should be employed and temperature control systems should be used where critical. (Ahmad, 2009) [33].

Cleaning-in-place (cip)

CIP or cleaning in place is used extensively for the interior cleaning of pipes, vessels, tankers, heat exchangers, fillers and other enclosed process systems. CIP involves a programed cycle including timed pre-rinse, cleaning and rinsing stages and can be fully automatic or semi-automatic with a system of valves, pumps and detergent tanks controlled by a microprocessor. There are a number of parameters that need to be specified and controlled for effective CIP such as flow parameters, pressure, temperature and detergent concentration (Pant *et al.*, 2023; van Asselt *et al.*, 2025) [26, 19].

Smart and Automated CIP Systems

In dairy and food processing facilities, intelligent and automated Clean-in-Place (CIP) technologies enhance cleaning effectiveness, consistency, and resource usage. Critical cleaning parameters like temperature, flow rate, chemical concentration, and cleaning duration are monitored and controlled by these systems using sensors and automated controls (Fryer & Asteriadou, 2009) [37]. Cleaning cycle optimization is made possible by real-time data collecting, which lowers water, energy, and chemical usage while upholding hygienic standards.

Enzymatic Cleaning

Enzymatic cleaning has emerged as a sustainable alternative to conventional chemical cleaning. Enzymes such as proteases, lipases, and amylases specifically target proteins, fats, and carbohydrates present in food residues. These cleaning agents can operate under milder conditions and reduce the need for harsh chemicals, high temperatures, and excessive water usage (Pant *et al.*, 2023) [19]. Enzyme-assisted CIP systems are increasingly being investigated for dairy applications because of their environmental benefits.

Plasma-Assisted and Advanced Cleaning Technologies

Recent advances in food sanitation have introduced plasmaactivated water, cold plasma treatments, ozone cleaning, and automated cleaning systems. These technologies provide enhanced microbial inactivation and biofilm removal while reducing chemical consumption. Plasma-assisted cleaning has shown considerable potential for improving cleaning efficiency and sustainability in dairy and food processing operations (de Souza *et al.*, 2024; Shah *et al.*, 2024) [5, 22].

Overall, the dairy and food industries employ a combination of cleaning methods depending on the nature of the processing equipment and hygiene requirements. While CIP remains the dominant cleaning approach for closed processing systems, COP, foam cleaning, dry cleaning, and emerging sustainable technologies continue to play important roles in maintaining food safety and operational efficiency.

Biofilm Formation and Detection in Milk Storage Tanks

Biofilm formation poses one of the most persistent microbiological challenges in dairy equipment sanitation. Biofilms structured communities of microorganisms encased in a self-produced extracellular polymeric matrix can adhere to stainless steel surfaces, pipeline interiors, and tank walls, resisting conventional cleaning and disinfection regimes. Organisms commonly implicated in dairy biofilms include *Pseudomonas fluorescens*, *Listeria monocytogenes*, *Bacillus cereus*, and thermophilic streptococci, all of which can contaminate milk and milk products if cleaning is inadequate.

The resistance of biofilms to CIP cleaning is welldocumented and reflects both the physical protection afforded by the extracellular matrix and the phenotypic tolerance of sessile organisms to biocidal agents. Standard alkali-acid CIP cycles, while effective against planktonic bacteria and loosely attached residues, may fail to remove mature biofilms, particularly in areas of low shear stress or poor spray coverage such as pipe bends, dead-legs, and agitator shafts.

Recent advances in biofilm detection include ATP bioluminescence assays, environmental sampling with PCRbased identification, and inline optical sensors capable

of detecting early-stage biofilm formation. These tools enable more targeted and timely intervention than conventional end-of-cycle microbiological swabbing. Some facilities have begun deploying inline biofilm sensors as part of their CIP control systems, allowing cleaning protocols to be triggered based on actual biological fouling status rather than elapsed time since the last cleaning cycle. Enzymatic cleaning agents capable of degrading the extracellular polymeric matrix of biofilms have also attracted research attention as adjuncts to conventional CIP formulations, although their cost and stability characteristics remain barriers to widespread adoption

Factors affecting the cleaning operation

The efficiency of cleaning operations in dairy and food processing industries depends on several interrelated factors that influence the removal of organic residues, mineral deposits, and microorganisms from food-contact surfaces. Effective cleaning is achieved through the optimization of chemical, physical, mechanical, and operational parameters, commonly represented by Sinner's Circle, which consists of temperature, chemical action, mechanical action, and contact time (Memisi *et al.*, 2015; van Asselt *et al.*, 2025) [26, 16].

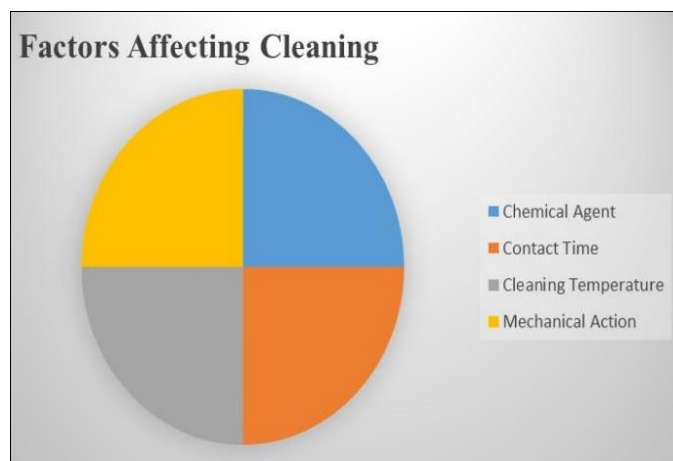


Fig 1: Factors Affecting Cleaning Operation

Chemical Agent

The type and concentration of cleaning chemicals directly influence the removal of food residues and microbial contaminants. Alkaline detergents are effective against proteins and fats, whereas acidic cleaners remove mineral scales and inorganic deposits. Insufficient chemical concentration may result in incomplete cleaning, while excessive concentrations increase operational costs and environmental impacts (Pant *et al.*, 2023; van Asselt *et al.*, 2025) [26, 19].

Contact time

Contact time refers to the duration for which cleaning agents remain in contact with the soil and equipment surfaces. Adequate exposure time is necessary for detergents to penetrate and dissolve deposits. When temperature,

chemical concentration, or mechanical action is reduced, longer cleaning are generally required to achieve comparable cleaning performance (van Asselt *et al.*, 2025) [26].

Cleaning temperature

Temperature is one of the most critical factors affecting cleaning performance. Elevated temperatures improve the solubility of fats, enhance chemical reaction rates, and reduce the viscosity of cleaning solutions, thereby increasing soil removal efficiency. However, excessively high temperatures may cause protein denaturation and stronger adhesion of residues to equipment surfaces, making cleaning more difficult (Memisi *et al.*, 2015; Pant *et al.*, 2023) [19, 16].

Table 1: Typical temperature ranges for detergent

Detergent Type	Temperature (°C)	Cleaning Task
Acid (HNO3)	60-65	Tanks, pipes, milk pasteurizers, etc.
Caustic (NaOH)	Cold to 40	Fermentation tanks, storage tanks, bright beer tanks, fillers.
Caustic (NaOH)	50-80	Higher temperatures are desirable, but problematic from a technical point of view.
Caustic (NaOH)	70-90	Milk collection tankers, milk tanks, cream tanks, quarg and yoghurt tanks, filling machines.
Caustic (NaOH)	90-130	Brewhouses, lauter tubs, mash tuns, wort coolers, milk pasteurizers, pipes, UHT plants,

Mechanical Action

Mechanical action facilitates the detachment and transport of soil from equipment surfaces. In CIP systems, mechanical action is provided by fluid turbulence, flow velocity, spray impingement, and circulation patterns. Increased turbulence enhances mass transfer and improves cleaning effectiveness, particularly in pipelines and heat exchangers (de Souza *et al.*, 2024; Memisi *et al.*, 2015) ^[5, 16].

Overall, successful cleaning operations depend on the proper balance of temperature, chemical concentration, mechanical action, and contact time, together with consideration of soil characteristics, equipment design, surface properties, water quality, and microbial contamination. Optimization of these factors is essential for ensuring food safety, maintaining product quality, and minimizing resource consumption in dairy and food processing industries.

Cleaning of storage tanks: Challenges and Complexities in Cleaning: Milk storage tanks are critical components of dairy processing systems, serving as temporary holding vessels for raw and processed milk before further processing or transportation. Maintaining the cleanliness of these tanks is essential for preserving milk quality, preventing microbial contamination, and ensuring compliance with food safety standards. However, effective cleaning of milk storage tanks presents several challenges due to the complex nature of milk residues and the design characteristics of storage vessels (Pant *et al.*, 2023; van Asselt *et al.*, 2025) ^[26, 19].

One of the major challenges is the accumulation of milk residues on tank surfaces. Milk contains proteins, fats, lactose, and minerals that readily adhere to stainless-steel surfaces during storage. Over time, these residues form persistent fouling layers that become increasingly difficult to remove, particularly when milk remains in contact with surfaces for extended periods or when cleaning is delayed (Bremer *et al.*, 2006) ^[1]. Protein deposits can denature and strongly adhere to surfaces, while fat residues may form hydrophobic layers that reduce the effectiveness of cleaning solutions (Pant *et al.*, 2023) ^[19].

Another significant challenge is the formation of milkstone, a hard mineral deposit primarily composed of calcium phosphate, calcium carbonate, magnesium salts, and milk proteins. Milkstone develops gradually on tank walls, weld joints, agitators, and other internal surfaces and cannot be effectively removed by alkaline cleaning alone. The presence of milkstone not only reduces cleaning efficiency but also creates rough surfaces that promote microbial attachment and biofilm development (Tamime, 2008; Bremer *et al.*, 2006) ^[1, 25].

Biofilm formation is considered one of the most critical sanitation challenges in milk storage tanks. Residual milk components provide nutrients that support microbial growth

on tank surfaces. Once microorganisms attach to surfaces, they can produce extracellular polymeric substances that form protective biofilms. These biofilms exhibit increased resistance to detergents and sanitizers and may serve as continuous sources of spoilage organisms and foodborne pathogens, including *Listeria monocytogenes*, *Bacillus cereus*, and *Pseudomonas* species (Carrascosa *et al.*, 2021; Chowdhury *et al.*, 2025) ^[4, 3].

The geometry of milk storage tanks further complicates cleaning operations. Large-capacity tanks often contain agitators, manholes, valves, weld seams, support structures, and shadow areas that are difficult to access during cleaning. These areas may experience insufficient turbulence and reduced detergent contact, leading to incomplete removal of residues and microorganisms (de Souza *et al.*, 2024) ^[5]. Dead zones and poorly designed fittings are particularly susceptible to residue accumulation and biofilm formation (Pejanovic *et al.*, 2026) ^[20].

Although Cleaning-in-Place (CIP) systems are widely used for milk storage tanks, they may not always provide sufficient mechanical action for removing stubborn deposits. Conventional spray-ball systems primarily rely on chemical action and fluid flow, which may be inadequate for heavily fouled surfaces or areas with limited spray coverage. As a result, residual deposits can persist despite repeated cleaning cycles, increasing water, chemical, and energy consumption (van Asselt *et al.*, 2025) ^[26].

The effectiveness of cleaning is also influenced by operational parameters such as cleaning solution concentration, temperature, contact time, and flow velocity. Improper optimization of these parameters may lead to incomplete soil removal or excessive resource consumption. In addition, frequent cleaning cycles generate substantial volumes of wastewater and contribute significantly to the overall water and energy requirements of dairy processing facilities (Pant *et al.*, 2023) ^[19].

Verification of cleaning effectiveness remains another challenge in milk storage tank sanitation. Visual inspection alone cannot reliably detect residual organic matter, microbial contamination, or biofilms. Therefore, industries increasingly employ ATP bioluminescence testing, microbiological analyses, conductivity measurements, and surface residue assessments to evaluate cleaning performance and validate sanitation procedures (Guerrero & Ríos Duarte, 2024) ^[8].

Consequently, there is growing interest in developing enhanced cleaning strategies for milk storage tanks, including improved spray devices, enzyme-assisted cleaning, plasma-based technologies, antimicrobial coatings, and supplementary mechanical cleaning approaches. These innovations aim to improve residue removal, reduce resource consumption, and overcome the limitations associated with conventional CIP systems (Pant *et al.*, 2023; van Asselt *et al.*, 2025) ^[26, 19].

Sustainability and Environmental Considerations in Tank Cleaning

The dairy industry faces growing pressure to reduce the environmental footprint of its cleaning operations, particularly with respect to water consumption, chemical discharge, and energy use. Water and energy recovery from CIP circuits has been identified as one of the highest-impact sustainability interventions available to dairy processors. Water reuse strategies such as capturing and treating final rinse water for use as pre-rinse water in subsequent cycles have been demonstrated to reduce CIP water consumption by 15-40% without compromising hygiene outcomes.

Membrane filtration and UV treatment technologies offer viable routes to water treatment and reuse in closed-loop systems. Thermal energy recovery from hot cleaning streams is also a proven approach; heat exchangers installed on CIP discharge lines can recover 60-80% of the thermal energy that would otherwise be lost (Klemes *et al.*, 2008) ^[11].

The development of enzymatic and bio-based cleaning

agents represents another area of active innovation. These agents target specific components of dairy soil proteases for protein residues, lipases for fat, and amylases for carbohydrate deposits and are formulated to be biodegradable and less corrosive to equipment surfaces than conventional alkali-acid formulations. Although their per-unit cost remains higher than conventional alternatives, lifecycle cost analyses that account for reduced water and energy use and extended equipment life are increasingly favourable.

The drive toward sustainability has also accelerated interest in reduced-frequency cleaning enabled by better hygienic design. By minimising dead-legs, horizontal surfaces, and crevices in tank design, the frequency and duration of required cleaning cycles can be reduced without compromising microbiological safety. This principle termed 'cleanability by design' is now embedded in updated hygienic design standards, including EHEDG and 3-A Sanitary Standards.

Table 2: Comparative Analysis of Cleaning Technologies

Cleaning Method	Principle	Advantages	Limitations	Water/Energy Use	Sustainability	Future Potential
Manual Cleaning	Physical scrubbing with cloths/brushes	Flexible; low capital cost; accessible for small operations	Labour-intensive; inconsistent results; chemical exposure risk	Low-moderate water use; no energy for automation	Limited; high labour input; chemical waste	Low; suitable for niche/small-scale applications
Foam Cleaning	Clinging foam penetrates crevices; detergent action	Good penetration of inaccessible areas; visual confirmation	Limited mechanical action; chemical foam disposal required	Moderate water; low energy	Moderate; biodegradable foam formulations available	Medium; potential for enzyme-based foam agents
Hydro Blasting	High-pressure water jet removes deposits	No chemical required; effective on hard deposits	High water consumption; energy-intensive; safety risks	Very high water; high energy	Low-moderate; wastewater treatment needed	Medium; water recycling systems can improve sustainability
CIP (Conventional)	Programmed chemical cycles through fixed pipework	Reproducible; minimal manual labour; validated	Fixed resource consumption; not adaptive to soil load	High water and energy use per cycle	Moderate; key target for optimisation	High; smart/automated CIP represents major improvement
Smart/Automated CIP	Sensor-driven dynamic adjustment of CIP parameters	Reduces water/chemical use 20-30%; improved consistency	High capital cost; requires skilled staff and digital infrastructure	Substantially lower than conventional CIP	High; data-driven optimisation reduces environmental burden	Very high; AI, IoT integration ongoing
Rotary Spray Balls	Rotating jets provide full tank surface coverage	Efficient coverage; lower chemical/water use than static	Moving parts need maintenance; biofilm risk in bearings	Lower than static spray; moderate energy	Good; less chemical required per clean	High; integration with smart CIP monitoring
Static Spray Balls	Fixed jets distribute cleaning solution by cascade	Simple; low cost; no moving parts	Relies on high volume/concentration; incomplete coverage	High water and chemical use	Low-moderate; high resource consumption	Low; being superseded by rotary and smart options

Table 2 provides a comparative overview of the principal milk storage tank cleaning technologies discussed in this review, evaluating each across dimensions of effectiveness, resource requirements, sustainability, and future development potential.

Note: This table represents a synthesis derived from the reviewed literature. Principal references informing the comparative assessments include: Tamime (2008) ^[25]; Moerman *et al.* (2014) ^[17]; Bremer *et al.* (2006) ^[11]; Klemes

et al. (2008) ^[11]; Blel *et al.* (2009); Vasadi (2014) ^[42]; and Holah and Lelieveld (2011) ^[43]. Assessments of smart/automated CIP are additionally informed by Hagiwara *et al.* (2022) ^[44] and Reinemann *et al.* (2023) ^[45]. Resource estimates represent ranges reported across multiple studies and should not be interpreted as universally applicable benchmarks; actual values will vary with facility scale, product type, and operational conditions.

Conclusion

This review has demonstrated that milk storage tank cleaning has evolved considerably from labour-intensive manual approaches to sophisticated, sensor-integrated automated systems. Conventional CIP remains the industry standard, but its fixed-cycle design is increasingly recognised as resource-inefficient relative to the cleaning task at hand. Smart CIP systems equipped with real-time turbidity, conductivity, and optical sensors offer a compelling pathway to maintaining or exceeding hygienic standards while reducing water consumption by 20-30% and chemical use by up to 25%. The integration of IoT platforms and machine learning into CIP management represents the next frontier, enabling predictive maintenance, anomaly detection, and dynamic protocol adaptation.

Biofilm management continues to be a major challenge. The development of enzymatic cleaning adjuncts, real-time biofilm detection tools, and hygienic design standards that minimise fouling-prone geometries are collectively strengthening the industry's capacity to address this threat. Meanwhile, sustainability imperatives are reshaping procurement and operational decisions, with water reuse systems, heat recovery from cleaning streams, and bio-based cleaning agents gaining traction as economically viable alternatives to conventional resource-intensive approaches. Future research should prioritise the development of standardised cleaning validation methodologies, long-term field evaluations of smart CIP technologies in diverse dairy settings including developing-country contexts and the assessment of novel biodegradable cleaning chemistries against established performance benchmarks. Continuous innovation in this domain is essential not only for product safety and operational efficiency, but for the long-term sustainability of the global dairy sector.

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