HILL PUBLISHING

International Journal of Food Science and Agriculture, 2025, 9(3), 173-185
https://www.hillpublisher.com/journals/jsfa/
ISSN Online: 2578-3475
ISSN Print: 2578-3467

Nanotechnology-enabled Approaches for Analyzing the Prevalence and Detection of Adulterants in Milk: A Scientific Study on Food Safety and Quality Control

Noor Zulfiqar[1,*], Muhammad Tayyab Shafi[2], Arifa Zafar[3], Areeba Sajjad[4], Shahab Ahmed[5], Satyadhar Joshi[6], Muhammad Waqas Hussain[7], Fawad Inam[8,9]

[1]Department of Chemistry, Faculty of Science, University of Agriculture, Faisalabad 38000, Punjab, Pakistan.
[2]Department of Engineering Management, Guglielmo Marconi University, Rome 00144, Italy.
[3]Department of Chemistry, Faculty of Science, Riphah International University, Faisalabad 38000, Punjab, Pakistan.
[4]Department of Pharmacy, The University of Faisalabad, Faisalabad 38000, Punjab, Pakistan.
[5]Dr. M.A. Kazi Institute of Chemistry, University of Sindh, Jamshoro 76080, Pakistan.
[6]Department Information Technology, Faculty Alumnus, Touro College, New York, NY 10010, USA.
[7]Assistant Food Safety Officer, Punjab Food Authority, Government of Punjab, Lahore 54000, Pakistan.
[8]School of Architecture, Computing and Engineering, University of East London, Docklands Campus, London E16 2RD, UK.
[9]Oxford Business College, Macclesfield House, Oxford OX1 1BY, UK.

How to cite this paper: Noor Zulfiqar, Muhammad Tayyab Shafi, Arifa Zafar, Areeba Sajjad, Shahab Ahmed, Satyadhar Joshi, Muhammad Waqas Hussain, Fawad Inam. (2025). Nanotechnology-enabled Approaches for Analyzing the Prevalence and Detection of Adulterants in Milk: A Scientific Study on Food Safety and Quality Control. *International Journal of Food Science and Agriculture*, 9(3), 173-185.
DOI: 10.26855/ijfsa.2025.09.004

Received: August 18, 2025
Accepted: September 15, 2025
Published: October 13, 2025

Corresponding author: Noor Zulfiqar, Department of Chemistry, Faculty of Science, University of Agriculture, Faisalabad 38000, Punjab, Pakistan.
Email: chemistnoor94@gmail.com

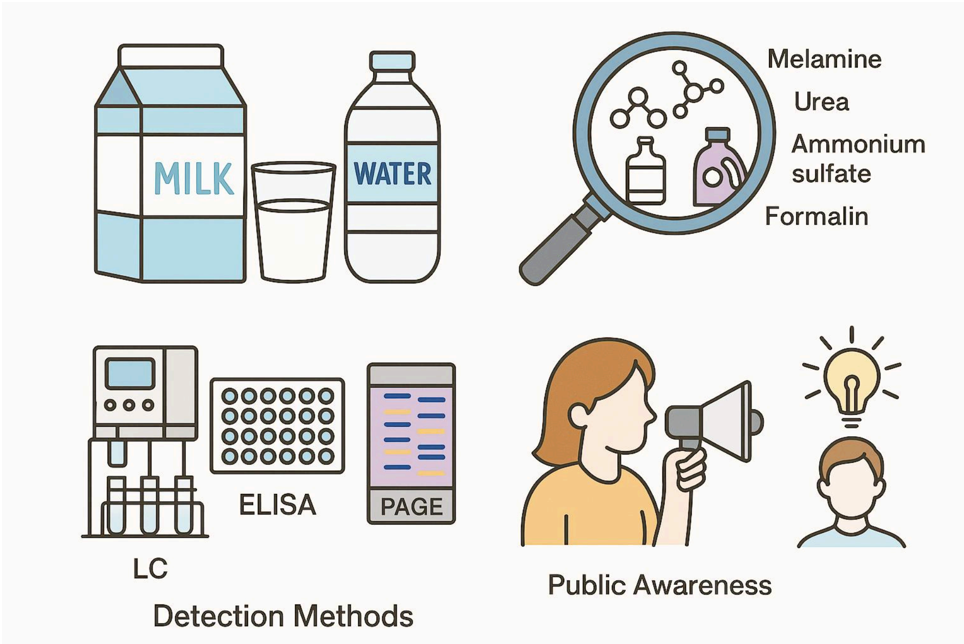
Abstract

Milk adulteration remains a critical public health concern worldwide, particularly in developing countries where regulatory oversight and detection infrastructure are often limited. Conventional methods, including basic chemical assays, provide rapid screening but lack the required sensitivity and specificity. Modern analytical techniques such as Liquid Chromatography (LC), Enzyme-Linked Immunosorbent Assay (ELISA), Polymerase Chain Reaction (PCR), and Polyacrylamide Gel Electrophoresis (PAGE) have significantly improved precision, yet their widespread application is hindered by cost and technical requirements. Recent advances in nanotechnology offer promising alternatives by enabling the development of highly sensitive, rapid, and cost-effective nano-biosensors, nanostructured substrates, and nanoparticle-based colorimetric assays for adulterant detection. These approaches enhance signal amplification, lower detection limits, and allow for point-of-care analysis even in resource-limited settings. This review integrates both conventional and emerging nano-enabled detection techniques, classifies adulterants into economically motivated (e.g., water, whey, vegetable proteins) and health-threatening (e.g., melamine, urea, detergents, formalin), and discusses their impact on milk's nutritional and safety parameters. Finally, the study emphasizes the urgent need for interdisciplinary strategies combining nanoscience, regulatory standards, and consumer education to ensure the safety and authenticity of dairy products.

Keywords

Milk adulteration; Food safety; Nanotechnology; Nano-biosensors, Qualitative detection; Quantitative analysis; Adulterants in milk; Public health risk; Chemical contaminants; LC and ELISA techniques; PCR and PAGE analysis; Dairy product quality; Synthetic milk; Food fraud; Regulatory standards; SNF manipulation; Melamine contamination

Graphical Abstract



1. Introduction

Adulteration in milk is a worldwide issue, and agricultural nations are at a greater risk because of the lack of checks and strategies. Nevertheless, this is one of the most widely recognized phenomena that has been ignored in numerous nations. Unfortunately, contrary to common belief, milk adulteration can pose serious human risks, prompting lethal illnesses. We will discuss a detailed review of normal milk adulteration, such as various techniques to distinguish the adulteration qualitatively as well as quantitatively. This review is structured with an adulterant-focused approach rather than a method-based one, where quantitative detection for the greater part of the regular adulteration is recruited and quantitative identification techniques are restricted to a few significant adulterations of the milk. Aside from the normal methods, ongoing improvement in these Identification procedures has likewise been reported [1]. Figure 1 shows a depiction of pure milk and adulterated milk.

Figure 1. A depiction of pure milk and adulterated milk.

After the discovery of melamine contamination in Chinese infant milk powder in 2008, the problem of adulteration of milk and dairy products became a global concern. However, the historical evidence for milk adulteration runs deep. As early as 1850, chewing gum adulteration was explained, and 8,000 babies died in New York City alone (in 1858, how we poisoned children's venom). Therefore, milk is considered "the ideal food" because two babies and two adults need a lot of extra milk products. It is perhaps the best hot spot for proteins, fats, starch, nutrients, and minerals. Unfortunately, milk is generally an effective adulterant around the world [2]. Figure 2 shows harmful effects of adulterants.

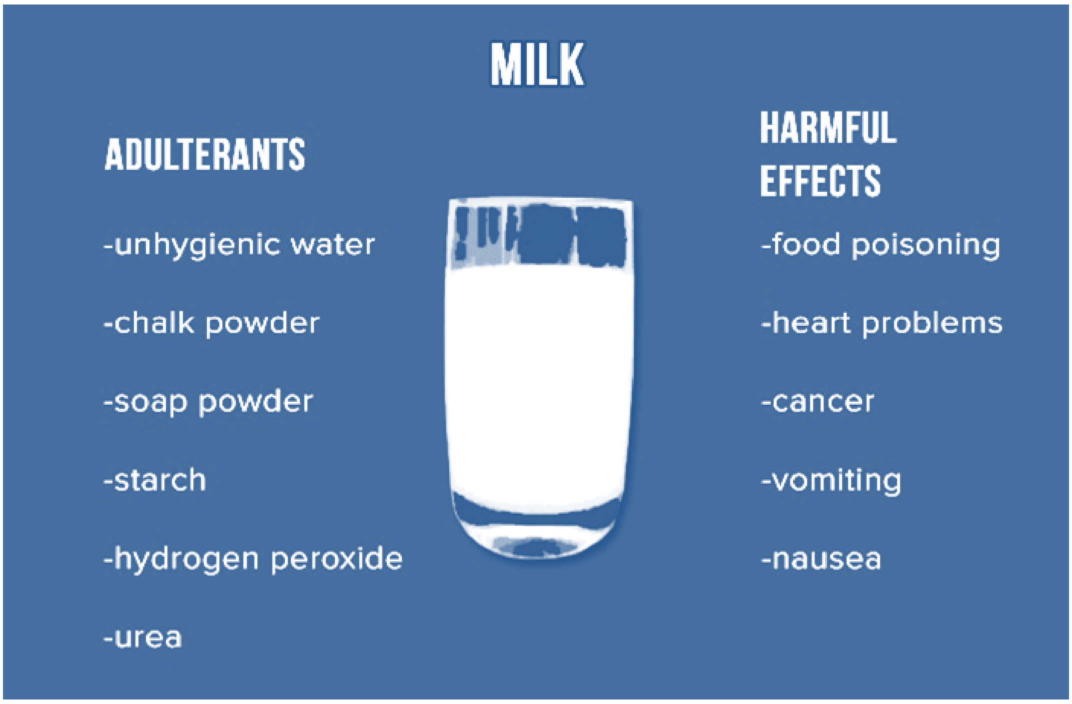


Figure 2. Harmful effects of adulterants.

Potential purposes for it might incorporate interest and supply hole, short shelf life of milk, low buying ability of the client, as well as absence regarding to appropriate Identification tests. The inspiration for food extortion is financial, yet the effect is a genuine general well-being concern. The circumstance is altogether more awful in creating and immature nations because of the nonexistence of sufficient checks and the absence of appropriate law enforcement. Qualitative identification of adulteration in milk may be handily accomplished with substance responses, and quantitative detection is complex and varied. The type of quantitative identification strategies depends upon the idea of adulteration in milk.

For instance, LC (Liquid Chromatography) and ELISA (Enzyme Linked Immunosorbent Assay) are the most widely recognized methods used to identify unfamiliar proteins [3, 4]; PCR (Polymerase Chain Reaction) and PAGE (Polyacrylamide Gel Electrophoresis) are normally used to distinguish milk from various species as adulteration in milk of specific animal categories. The DMAB test (p-dimethylaminobenzaldehyde test) is a widely used qualitative method for detecting urea adulteration in milk. Urea is frequently added to milk to artificially enhance its solids-not-fat (SNF) content and mimic higher protein levels, posing serious health risks such as kidney damage and metabolic imbalance. In this test, an aqueous solution of p-dimethylaminobenzaldehyde (DMAB) reacts with urea under acidic conditions to produce a distinct yellow-colored complex. The appearance of this yellow color confirms the presence of urea in the milk sample [5].

The DMAB test is simple, rapid, and inexpensive, making it suitable for routine field-level screening of milk quality. However, it is semi-quantitative at best and cannot provide precise concentration levels of urea. For accurate quantification, more advanced methods such as Liquid Chromatography (LC), Gas Chromatography coupled with Isotope Dilution Mass Spectrometry (GC/IDMS), or FTIR spectroscopy are preferred. Nevertheless, the DMAB test remains an important preliminary tool in milk adulteration studies, especially in regions where advanced analytical infrastructure is limited [6]. Milk adulteration discovery procedures should be unmistakable and fast, since defrauders have gotten away from judgment, asserting less adequacy of the regular detection methods [7].

Table 1. Common Milk Adulterants and Their Effects

Adulterant	Used To	Detection Method	Health Hazards
Water	Increase milk volume	Lactometer test	Dilution of nutrients, affects infant nutrition
Detergent	Mimic fat content & emulsify	Phenol red test	Gastrointestinal irritation, toxicity
Urea	Raise SNF and non-protein nitrogen	DMAB test, LC, GC/IDMS	Kidney damage, nausea, vomiting
Formalin	Preserve milk shelf life	Sulphuric acid test	Carcinogenic, liver and kidney damage
Ammonium sulfate	Alter lactometer reading	Spectroscopic detection	Digestive distress, liver damage
Melamine	Mimic protein content	SERS, LC-MS/MS, HPLC	Renal failure, especially in infants
Starch	Increase SNF content	Iodine test (blue color)	Dangerous for diabetic patients
Salt	Enhance taste and density	Silver nitrate test	High blood pressure, heart stress
Sugar	Increase SNF falsely	Benedict's reagent test	Safe in small amounts, bad for diabetics
Boric acid	Preserve milk	Turmeric paper test	Nausea, vomiting, organ failure at high doses
Hydrogen peroxide	Increase shelf life	Chromogenic or UV detection	Mouth, throat, stomach irritation
Synthetic milk	Economic fraud	Sensory analysis, pH, fat test	Contains harmful detergents & urea
Vegetable proteins	Increase protein content	ELISA, PAGE	Potential allergen, nutritional deficiency
Milk from other species	Economic fraud	PCR, PAGE, ELISA	Allergic reactions, mislabeling issues

In recent years, nanotechnology has emerged as a revolutionary platform for food quality monitoring. Owing to their unique physicochemical properties, nanomaterials such as gold nanoparticles, carbon nanotubes, and graphene-based composites have been employed to design highly sensitive and selective sensors for milk adulteration detection. These nano-enabled systems allow for real-time analysis, require minimal sample preparation, and can be integrated into portable devices, making them particularly useful in resource-limited settings [8, 9].

Table 2. Nano-Enabled Detection Techniques for Milk Adulteration

Nanotechnology Approach	Target Adulterant(s)	Working Principle	Advantages	Limitations
Gold & Silver Nanoparticles (Colorimetric Assays)	Melamine, Urea, Detergents	Color change due to nanoparticle aggregation in presence of adulterant	Simple, rapid, visible to naked eye	Mostly qualitative; sensitivity depends on nanoparticle stability
Graphene & Carbon Nanotube Sensors	Urea, Formalin, Heavy Metals	Electrochemical sensing via enhanced electron transfer at nano-surfaces	Ultra-sensitive, reusable, portable	Requires electrode modification; may need calibration
SERS (Surface-Enhanced Raman Spectroscopy)	Melamine, Formalin, Protein Adulterants	Raman signal amplification using nanostructured metallic surfaces	Ultra-trace detection, label-free	High instrumentation cost
Quantum Dots (Fluorescent Probes)	Melamine, Ammonium Sulfate	Fluorescence quenching/enhancement upon interaction with adulterant	High sensitivity, rapid readout	Photobleaching, stability issues

Table 2 Continued

Nanotechnology Approach	Target Adulterant(s)	Working Principle	Advantages	Limitations
Metal–Organic Frameworks (MOF)-Based Sensors	Melamine, Urea	Selective adsorption and fluorescence response of nano-porous MOFs	High selectivity, tunable	Expensive synthesis; less field-tested
Nano-Biosensors (Enzyme/Antibody Functionalized)	Urea, Protein Adulterants, Species Identification	Biorecognition element immobilized on nanomaterial for electrochemical or optical detection	Highly specific, real-time response	Enzyme/antibody stability may limit shelf life

2. Standard Adulterants within Milk

Powdered milk is another food thing being in the danger of adulteration after the olive oil. Adulteration in milk for the most part incorporate expansion of vegetable protein, milk from various species, expansion of whey and watering which are known as financially propelled adulteration [10]. These adulterations don't represent any extreme wellbeing hazard. Nonetheless, a few adulterations are too hurtful to ever be ignored. A portion of the significant adulteration in milk having genuine unfavorable wellbeing impact are urea, formalin, cleansers, ammonium sulfate, boric corrosive, harsh pop, benzoic corrosive, salicylic corrosive.

Fat rate (Stable), protein substance, and point of freezing are the specific limits that are tested to determine milk consistency. Milk is used in adulteration to extend these limits, consequently deceptively expanding the content of milk. Pure sweetener, sugar, sulfate salts, urea, and regular salts are introduced to extend solid non-fat salts, for example (SNF). Urea has the largest cutoff prescribed by the FSSAI (Agricultural Marketing Association of India) Act 2006 and Protection of milk Adulteration Rules in 1956, being a typical constituent of synthetic milk [11]. To raise the content of non-protein nitrogen, commercial urea is pasteurized. In addition, melamine, is artificially introduced to increase the quantity of protein. To extend the curating lactometer by holding up the thickness of depleted milk, ammonium sulfate is introduced. As contaminants, formaldehyde, salicylic toxic, benzoic poisonous & hydrogen peroxide go around & improve time cycle of milk usefulness [6]. Figure 3 depicts a laboratory technique for quantitative detection of milk adulteration.

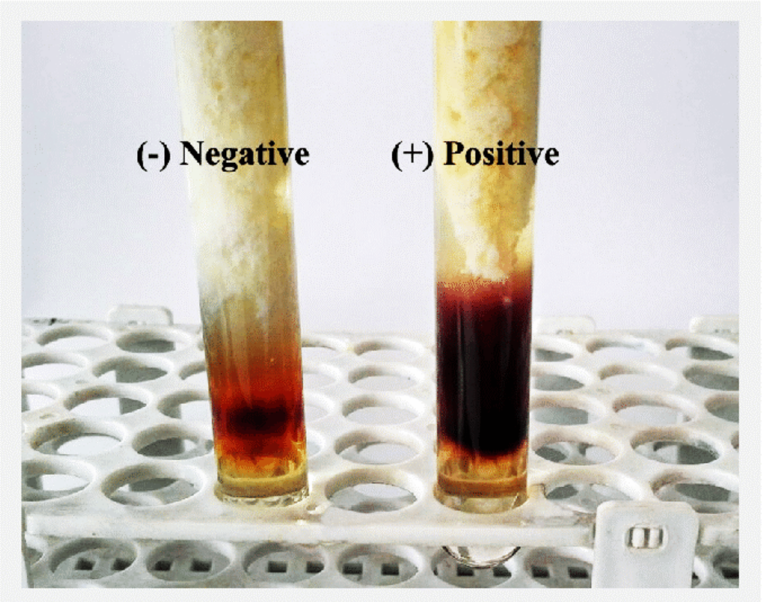


Figure 3. Image depicting laboratory technique for quantitative detection of milk adulteration.

Since fat content is costly, a few milk and dairy producers extract fat content for extra monetary benefit and by adding—anti-fat, such as ghee, refund it by for example. To dissolve the sugar and split up the oil in water, cleansers are applied to give a soupy condition, and that is the perfect milk features. Unfortunately, a part of the adulteration, in some cases, over the long term, has a severe effect on health. Melamine use at levels as high as 40 mg/kg will cause renal failure and mortality in infant babies. The two peroxides and cleansers in milk, which can cause gastritis and irritation of the digestive tract, can cause gastro-intestinal problems. Excessive starch in the milk can induce runs because of the effects of undigested starch in the colon, but accumulated starch in the body will prove extremely dangerous for diabetic patients [12]. When more urea content from the body has to be sealed in, urea in milk overburdens the kidneys. Hormone-blocking disturbances that control enhancement and replication may also be caused by carbonates and bicarbonates.

3. Qualitative Identification Procedures

Qualitative identification of adulteration in dairy milk is the basic colour based reactions of chemicals. It can be performed in a Laboratory with accessibility of synthetic reagents and fundamental safety measures. Significant disadvantages of these strategies are the realities that these are legitimate for a restricted scope of focuses and are not adequately exact. Nonetheless, qualitative Identifications are favorable in light of the fact that these are straightforward, fast and simple to perform. A portion of the pleasant and tasty compounds are regularly use as adulteration to improve the flavor of the milk. Be that as it may, there are some dangerous synthetics included milk to improve the actual appearances and time span of usability. A portion of those is risky and can prompt deadly infections. Moreover, some other blended synthetic substances, for example, cleanser, cleansers and shading mixes are here and there infused to the milk for appearance enhancement [3].

While traditional qualitative tests are simple and inexpensive, their limited specificity necessitates advanced alternatives. Nanotechnology-based colorimetric assays, often employing metallic nanoparticles that exhibit distinct color changes upon interaction with adulterants like melamine or urea, represent a promising advancement. Such nano-enabled tests combine the simplicity of conventional colorimetric methods with enhanced precision, thereby bridging the gap between laboratory-based and field-level detection [13-15].

4. Milk Adulteration with Foreign Proteins

Corn, wheat, and coconut proteins are intentionally treated into milk-like products for users with lactose intolerance and sold as milk substitutes. Nevertheless, soy, wheat and almond proteins are labeled as allergens in the Food Allergen Labeling & User Protection of 2004, whereas pea, corn, lupine and maize proteins are clinically perceived as allergens. The manner in which the cost of producing soy milk is 70% lower than regular milk and protein from soybean oil is considerably less costly than milk protein, causes soy milk producers to taint milk. Polarization methods are a popular identification technique for soy milk [16],

- isoelectric precipitation,
- Sodium Dodecyl Sulfate,
- Polyacrylamide Gel Electrophoresis,
- HPLC (High Performance Liquid Chromatography) and,
- immunodiffusion strategy.

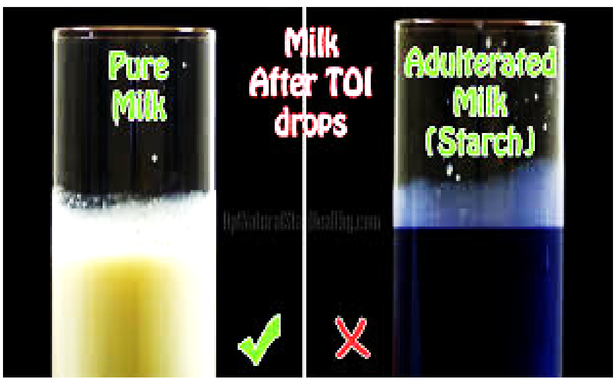


Figure 4. An illustration of pure milk and milk adulteration with starch.

Nir (Near Infra-Red) mass spectrometry has been used to detect the adulteration of milk powder with polyunsaturated fats. Homogenized or UHT (Ultra High Temperature) powdered milk adulteration with corn, sweet potato, and rice proteins was responsible for [17].

To detect these proteins with foreign proteins, ELISA was used. Using UHPLCC, sheared milk powder was efficiently separated using wheat, sweet potato, earthy coloured rice, and dehydrated corn starch (Ultra High-Performance Liquid Chromatography). Procedures based on mass spectroscopy to identify milk protein complexes have been published. Tetraborate-EDTA variability assistance for the isolation of plant proteins from milk was used to establish a rapid colorimetric recognition method for the differentiation of insoluble plant proteins [18]. Figure 4 is an illustration of pure milk and milk adulteration with starch.

5. Adulteration of Milk by Milk from Various Sources

Due to the frequent adulteration of milk with content from non-conventional sources, including milk from different animal species, the accurate identification of such adulteration based on genetic and non-genetic polymorphisms has become a critical challenge. Quantitative analysis plays a key role in ensuring authenticity. In this context, the use of Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) has proven to be a feasible method for verifying the natural origin of milk [19].

This technique analyses the different metals (inorganic metals and non-metals) of the milk in addition to isotope proportion mass spectrometry (IRMS) and identifies geological comparisons using chemometric methods based on multinomial observable techniques. HPLC chromatographic techniques have tested milk protein adulteration in caprine milk [20].

This technique considers sub-atomic masses to differentiate between cow and goat milk proteins. The extension of bovine milk into goat and sheep milk has been established. Due to the fact that (Protected Classification of Origin) cheeses are the product of high market esteem, restricted by authoritative and acceptable labeling laws, various scientific techniques have been introduced to determine credibility. In terms of the unstable phenotype, analysis and adulteration evaluation of lamb, mammalian, and Drosophila milk variations in company PDO cheeses is analyzed using RP-HPLC (Reversed-phase High Performance Liquid Chromatography) [21], an elevated liquefying (HRM) based strategy using clear mitochondrial preliminaries and heavy stage membrane separation spectrometry technique (SPME-MS) [22]. Roundabout Extreme ELISA has been applied to identify adulteration in milk of cow, lamb, and bison milk from dairy animals.

Using PCR, caprine milk adulteration from cow milk has also been differentiated [23]. Furthermore, in goat milk, goat butter, and wild cow pesto goat cheese, PCR was used to differentiate cow's milk. In lamb milk, which is capable of perceiving 5 simple flavor standards, has been applied to discern milk adulteration of caprine. This is an elective approach to conventional methods of insight. The individual protein selection was broken down using PAGE. Cow-like milk development in goat milk and cow milk has also been tested with PAGE. It is more important in these applications to use IES (Isoelectric Focusing) rather than PAGE. Serological and DNA-based techniques have been combined to classify one explicit nucleotide found in bovine milk as adulteration in ewe, goat, and bison milk as PCR-LCR-EIA (Nucleic Acid - Ligase Chain Reaction-Enzyme Immunoassay) [24]. In lamb, ewe, and goat milk, lipophilic practical chromatography is used for the distinction and confirmation of various proteins. The difference between pure milk and adulterated milk is shown in Figure 5.

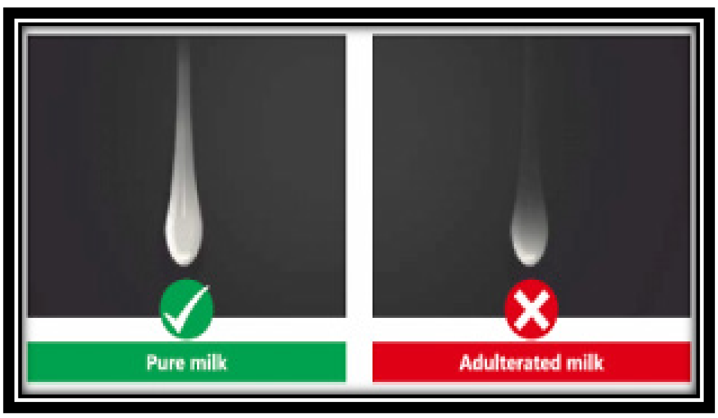


Figure 5. Pure Milk Vs Adulterated Milk.

6. Adulteration in Milk with Melamine

Since melamine is neither an approved substance nor a food fixative, it was not until 2008 when melamine contamination was reported in China that the key points in the food law were known. The European Commission and the United States Food and Drug Administration (USFDA) have also set the upper limit of melamine in foreign foods to 2.5 mg/kg, and the upper limit of melamine in the new formula to 1 mg/kg. Born. Later, the Codex Alimentarius Commission of the United Nations Food Quality Agency recognized this and passed a further decision in 2010, reflecting that melamine is not only used as adulteration in excrement meal, but also includes a variety of different foods, such as wheat gluten, chicken feed, and processed food sources.

Nanotechnology has played a pivotal role in advancing melamine detection. Surface-Enhanced Raman Spectroscopy (SERS) based on silver or gold nanostructures significantly amplifies Raman signals, enabling detection of melamine at trace levels. Similarly, nano-engineered fluorescent probes and metal–organic framework (MOF) nanosensors have demonstrated rapid, ultra-sensitive, and reliable screening for melamine in milk powder, thereby surpassing the limitations of conventional chromatography-based methods [25-27]. Figure 6 depicts adulteration in milk with melamine.

Figure 6. Adulteration in milk with melamine.

Regarding the fact that it does not cause cancer, under special circumstances, it can cause kidney damage and child death. Quantitatively, SERS (Surface Enhanced Raman Spectroscopy) can be used to detect melamine. A practical sensor that relies on SERS has been developed to automatically detect melamine. In order to test the melamine in liquid milk and milk powder, SB-ATR FTIR (single reflection attenuated total Reflection-Fourier transform infrared spectroscopy) was used [28]. Various kinds of mass spectroscopy have been used in milk products to detect melamine, including:

- LC-MS/MS,
- APCI-MS (Atmospheric Pressure Chemical Ionization-Mass Spectroscopy) and,
- EESI-MS (Extractive Electrospray Ionization Mass Spectrometry)

Melamine in milk powder is easy to detect without the need to use a 676 cm-1 Raman band to remove melamine from milk. To test melamine, a flexible screening system based on Raman laser spectroscopy has been developed. Gold nanoparticles whose surface is bonded with melamine and have a secondary cyanuric acid etchant have been constructed. After the official appearance of melamine, these nanoparticles suddenly changed their hue from red to blue, which can be used as a technology to discover melamine. In addition to customary methodology, such as GC-MS, the use of an oxidized polycrystalline gold cathode was accounted for to classify melamine. Latest developments in the discovery of melamine have been investigated [29]. LC-MS/MS has been used as far as possible to distinguish melamine in milk from various components of newborns. Another strategic decision for evaluating melamine in milk and dairy products is HPLC.

Table 3. Advanced Detection Techniques for Milk Adulteration

Technique	Used For	Working Principle	Advantages	Limitations
LC	Urea, melamine	Separates compounds based on polarity	Accurate and sensitive	Expensive, requires skilled operators
HPLC	Protein adulteration, species ID	High-pressure analyte separation	High resolution	Costly equipment
ELISA	Foreign proteins, allergens	Antibody-antigen binding	Specific and rapid	May miss unknown adulterants
PCR	Species-specific adulteration	DNA amplification	Highly specific	Requires laboratory setup
PAGE	Protein profiling	Electrophoretic separation	Simple and cost-effective	Low sensitivity for some proteins
SERS	Melamine	Raman signal enhancement on nanostructures	Ultra-sensitive, label-free	Instrumentation complexity
GC/IDMS	Urea	Chromatography with isotope dilution MS	Precise quantification	Sample preparation intensive
FTIR	Various adulterants	Infrared absorption	Non-destructive	Overlapping spectra can reduce clarity
NIR	Vegetable oils, whey	Near-infrared spectroscopy	Fast, low sample prep	Calibration needed
Colorimetric Sensors	Urea, melamine	Color change via chemical interaction	Easy to use	Qualitative, not quantitative

7. Milk Adulteration with Urea

The known present value of non-protein nitrogen in milk is calculated from urea, which is a characteristic component of milk. According to the 2006 FSSAI method and the 1955 PFA regulations, the maximum discount point for urea in milk is 70 mg / 100 ml. urea and imprecise milk development are provided for typical milk [30]. The mass spectrometry method is similar to the infrared method and is used to determine the presence of urea without any pre-treatment. LC is used to calculate the adulteration of milk with urea. To test for urea in milk, a GC/IDMS-related technique (gas chromatography/isotope dilution mass spectrometry) was used. To identify the appearance of normal urea in milk, it is recommended that urea be converted to a derivative containing a hair chromophore prior to checking by HPLC [31].

To detect the adulteration of milk with melamine, urea, and ammonium sulfate, as illustrated in Figure 7, a spectroscopic technique has been proposed. Specifically, six distinct analytical strategies have been developed for the detection of urea, each optimized for varying experimental conditions and stress parameters. At the patented frequency of 1530 nm, the infrared beam retains alkali. The standard is used in a light waveguide sensor integrated in a PCB, which can detect a wide range of analytes, including acetic acid. A FET field-effect transistor-based gas sensor with a graphene channel and an IL (ionic liquid) gate was constructed to detect odour salts at 30 ppm and carbon dioxide at 4000 ppm in both cases. With an input voltage of less than 1V, it can be used to identify urea in milk. To identify urea in milk, where a straight line has been identified between the same electrical signal and the measurement of the odour of gaseous salts, a chemical-based piezoelectric sensor has been developed. To identify urea, the response-dependent enzyme potential bio-sensor EISCAP (electrolyte insulator semi-conductor capacitor) was developed. All other biosensors have just been developed for the identification of urea in milk according to various criteria such as voltage measurement, chemistry, and potential dynamic polarization [31-32].

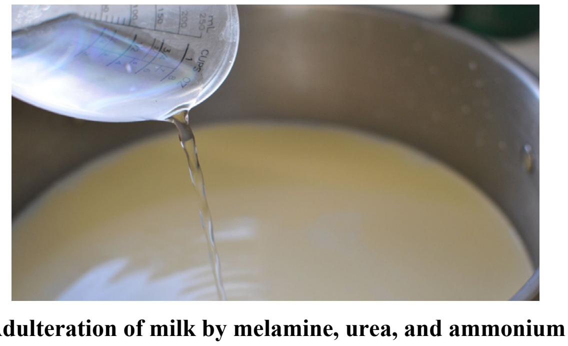


Figure 7. Adulteration of milk by melamine, urea, and ammonium sulphate.

8. Milk Adulteration with Different Other Compounds

Different spectroscopic techniques, including Mid-Infrared (MIR) spectroscopy and Near-Infrared (NIR) spectroscopy, have been applied to detect dilution with water or the addition of whey proteins in milk. Santos set up a flexible spectrometer in a near-test focus between different spectroscopic techniques and noted that MIR worked in a way that is much better than other methods to detect adulteration, such as faucet water, whey, hydrogen peroxide, lactic acid, and pee created. In fact, engineered urine is used in milk to increase the nutrient content, much like urea. In all cases of adulterer milk, pee was detected by a photometric method in a situation analysis performed in Brazil [33-34]. A procedure using infrared micro spectroscopy and chemometric analysis can discern the identity of processed pee up to a grouping of 0.78 mg/L of milk. For the development of a compact and operated infrared beam for milk research, a comparable technique has been considered to be used.

In addition, the presence of urine was accounted for by observing variations in the accumulation of sodium & calcium in fire nuclear retention spectroscopy cases. For assessing vegetable oil in milk, NMR MS was used. It was also feasible to detect numerous adulterations using Raman synthetic technology, including copper sulphate, urea in powdered milk. In addition, milk fat adulteration is an extremely critical challenge; in any case, a few methods have been introduced to identify adulteration based on Refractometer fluorescence spectroscopy, mass spectroscopy, and Raman spectroscopy.

9. Public Awareness and Consumer Responsibility

Public awareness is a crucial component in addressing the widespread issue of milk adulteration. Despite the severe health risks posed by adulterated milk, many consumers, especially in developing countries, lack sufficient knowledge about common adulterants, their harmful effects, and methods to detect them. This gap in awareness allows unethical practices to persist unchallenged within the dairy supply chain. To empower consumers, it is essential to integrate food safety education into public health campaigns, community workshops, and educational curricula. Simple, low-cost household tests for detecting adulterants such as starch, detergents, urea, and formalin can be demonstrated through public service announcements, mobile applications, or printed guides distributed in markets and rural areas. Involving local health workers, teachers, and community leaders in awareness efforts can also improve outreach, particularly in low-literacy populations.

Furthermore, consumer choices can drive industry accountability. By demanding certified milk products, checking for quality seals (e.g., ISO, FSSAI, or national food safety certifications), and reporting suspicious vendors, consumers play a vital role in shaping safer market practices. Encouraging collective consumer action, such as forming community monitoring groups or citizen science initiatives, can amplify efforts to hold suppliers accountable. Ultimately, building a culture of informed consumption is key to disrupting the cycle of adulteration. Consumers must recognize their right to safe food and their power to influence the system through awareness, vigilance, and responsible purchasing behavior.

10. Recommendations

To comprehensively address the challenge of milk adulteration, a coordinated strategy involving technological, regulatory, industrial, and societal actions is necessary. The following recommendations offer a roadmap for improving milk safety and protecting public health:

(1) Strengthen Food Safety Regulations
Governments should update and enforce national food safety laws that clearly define acceptable milk composition, set legal limits for contaminants, and classify milk adulteration as a criminal offense. Routine inspections and surprise sampling of milk vendors and processing units must be intensified.

(2) Implement Robust Surveillance Systems
Establish centralized food safety monitoring systems that integrate laboratory testing, field inspections, and real-time data collection to identify and respond quickly to adulteration incidents.

(3) Develop and Distribute Rapid Testing Kits
Affordable, portable milk testing kits should be distributed to households, schools, local dairy cooperatives, and inspection teams. These kits should be user-friendly, giving quick visual indications of specific adulterants without requiring advanced laboratory skills.

(4) Promote Research and Innovation in Detection Technologies
Invest in the development of advanced detection methods such as biosensors, nanotechnology-based detectors, and AI-driven diagnostic tools that offer real-time, accurate analysis at low cost. Collaboration with academic institutions can accelerate innovation.

(5) Encourage Industry Transparency and Accountability
Dairy companies should be mandated to maintain traceability across the supply chain, conduct regular internal quality audits, and disclose testing reports. Certification programs and incentive-based recognition for high-quality producers can promote ethical behavior.

(6) Enhance Public Awareness and Outreach
Launch nationwide campaigns to educate the public on the dangers of milk adulteration, focusing on rural and semi-urban populations. Use mass media, social platforms, community radio, and school-based programs to reach diverse demographics.

(7) Establish Consumer Feedback and Reporting Mechanisms
Implement helplines, mobile apps, or QR-code-based platforms where consumers can report suspected adulteration or lodge complaints. These systems should be monitored by regulatory authorities for prompt action.

(8) Strengthen Capacity Building and Training
Provide training for dairy farmers, milk handlers, and vendors on hygienic handling practices, safe milk preservation, and the legal consequences of adulteration. Empower local institutions to act as watchdogs of quality assurance.

(9) Support Grassroots and NGO Involvement
Collaborate with non-governmental organizations and civil society to mobilize communities and conduct independent milk testing campaigns, especially in regions with limited access to government oversight.

(10) Foster International Collaboration
Engage in global knowledge-sharing platforms, collaborate with international food safety agencies (e.g., FAO, WHO, Codex Alimentarius), and adopt international best practices for milk quality monitoring and regulation.

(11) Promote Nano-Enabled Detection Technologies
Encourage research and industrial adoption of nano-biosensors, SERS substrates, graphene-based electrochemical sensors, and MOF-derived platforms for routine milk adulteration testing. These nano-enabled devices offer high sensitivity, portability, and cost-effectiveness, making them ideal for both laboratory and consumer-level applications. Integrating nanotechnology into national food safety frameworks can significantly enhance detection efficiency and early warning systems [35-37].

These multi-pronged interventions spanning detection, regulation, education, and accountability can significantly reduce milk adulteration risks. A joint effort among government bodies, industry players, researchers, and the general public is essential to ensure access to safe, nutritious, and unadulterated milk for all.

10. Conclusion

Milk adulteration, driven by economic incentives and demand-supply gaps, continues to jeopardize food safety and public health, particularly in developing regions with weak regulatory enforcement. Conventional detection techniques, though widely used, are inadequate to cope with the evolving complexity of adulterants. High-end laboratory-based methods such as ELISA, PCR, LC, and PAGE remain indispensable, but their accessibility is limited. The integration of nanotechnology into milk adulteration detection offers a transformative solution, providing ultra-sensitive, selective, and rapid analysis through nano-biosensors, nanoparticle-assisted assays, and SERS-based platforms. These nano-enabled approaches can bridge the gap between laboratory precision and consumer-level accessibility, allowing real-time monitoring and point-of-care detection. Alongside technological innovation, strong regulatory action, consumer education, and industry accountability are equally crucial to mitigate risks. A synergistic strategy combining nanoscience-driven detection technologies with public awareness and robust governance can significantly reduce adulteration practices and ensure safe, nutritious, and authentic milk for global populations.

References

[1] Das S, Goswami B, Biswas K. Milk adulteration and detection: a review. Sensor Letters. 2016;14(1):4-18.

[2] Jun-shi C. A worldwide food safety concern in 2008-melamine-contaminated infant formula in China caused urinary tract stone in 290,000 children in China. Chin Med J (Engl). 2009;122(3):243-4.

[3] Chen RK, Chang LW, Chung YT, Lee MH, Ling YC. Quantification of cow milk adulteration in goat milk using high‐performance liquid chromatography with electrospray ionization mass spectrometry. Rapid Commun Mass Spectrom. 2004;18(10):1167-71.

[4] Ilisz I, Berkecz R, Péter A. Application of chiral derivatizing agents in the high-performance liquid chromatographic separation of amino acid enantiomers: a review. J Pharm Biomed Anal. 2008;47(1):1-15.

[5] Mahipalsinh C, Solanki JJ, Patel PS, Patel VK, Prajapati KB. Evaluation of DMAB test for detection of urea mixed in milk and improvement in its efficacy. 2017.

[6] Azad T, Ahmed S. Common milk adulteration and their detection techniques. Int J Food Contam. 2016;3(1):22.

[7] Mayer HK. Milk species identification in cheese varieties using electrophoretic, chromatographic and PCR techniques. Int Dairy J. 2005;15(6-9):595-604.

[8] Zulfiqar N, Nadeem R, Musaimi OAI. Photocatalytic Degradation of Antibiotics via Exploitation of a Magnetic Nanocomposite: A Green Nanotechnology Approach toward Drug-Contaminated Wastewater Reclamation. ACS Omega. 2024.

[9] Zulfiqar N, Shariatipour M, Inam F. Synthesis of metal nanoparticles and their role in degradation of pesticides/herbicides: a review. Discov Appl Sci. 2025;7(6):1-24.

[10] Islam MM, Mandal MK. Food Safety, Effects of Adulterated Food on Health, and Some Simple Methods of Detection of Adulteration in Some Common Food Items. In: Dietary Supplements and Nutraceuticals. Springer; 2025:1-29.

[11] KENDRA DDUK. B. Voc/B. Voc (Honours) Food Testing and Quality Evaluation (Effect from July 2024).

[12] Sen S, Ghosh S, Dutta SJ, Biswas R, Mazumder N. Qualitative And Quantitative Analysis For Adulteration And Nutritional Value Of Milk: A Case Study. Neuroquantology. 2022;20(17):227-37.

[13] Dutta SJ, Das U, Biswas R, Mazumder N. Development of a predictive model for determination of urea in milk using silver nanoparticles and UV–Vis spectroscopy. LWT. 2022;168:113893.

[14] Zulfiqar N, Shariatipour M, Inam F. Sequestration of chromium (vi) and nickel (ii) heavy metals from unhygienic water via sustainable and innovative magnetic nanotechnology. Nanoscale Adv. 2024;6(1):287-301.

[15] Zulfiqar N. Magnetic Marvels: Comparative Synthesis and Characterization of Multifaceted Nanoscale Magnetic Particles for Innovative Applications. J Nanomed Nanotechnol. 2024;15(2):721.

[16] Momtaz M, Bubli SY, Khan MS. Mechanisms and health aspects of food adulteration: A comprehensive review. Foods. 2023;12(1):199.

[17] Yang R, Huang W, Zhang L, Thomas M, Pei X. Milk adulteration with melamine in China: crisis and response. Qual Assur Saf Crops Foods. 2009;1(2):111-6.

[18] Yang J, Zheng N, Wang J, Zhang Y, Zhao S, Yang Y, et al. Detection of plant protein adulterated in fluid milk using two-dimensional gel electrophoresis combined with mass spectrometry. J Food Sci Technol. 2018;55(7):2721-8.

[19] Kiani A, Arabameri M, Moazzen M, Shariatifar N, Khaniki GJ, Abdel-Wahhab MA, et al. Probabilistic health risk assessment of trace elements in baby food and milk powder using ICP-OES method. Biol Trace Elem Res. 2022;200(5):2486-97.

[20] Brox S, Seiwert B, Kästner K, Huber C, Kuballa T, Reemtsma T. A quantitative HPLC-MS/MS method for studying internal concentrations and toxicokinetics of 34 polar analytes in zebrafish (Danio rerio) embryos. Anal Bioanal Chem. 2014;406(20):4831-40.

[21] Tormo M, Izco J. Alternative reversed-phase high-performance liquid chromatography method to analyse organic acids in dairy products. J Chromatogr A. 2004;1033(2):305-10.

[22] Yue J, Zheng Y, Liu Z, Deng Y, Jing Y, Luo Y, et al. Characterization of volatile compounds in microfiltered pasteurized milk using solid-phase microextraction and GC× GC-TOFMS. Int J Food Prop. 2015;18(10):2193-212.

[23] Tsakali E, Angelika-Ioanna G, Voutsinas L, Pletsa D, Koulourida V, Eliopoulos C, et al. Milk adulteration: detection of bovine milk in caprine dairy products by real time PCR. J Food Res. 2019;8(4):52-7.

[24] Patil GB, Patil SM, Bhavsar SN, Patil AP, Patil SS, Patil PS. Milk adulteration: From detection to health impact. Food Humanit. 2024;3:100339.

[25] Das U, Biswas R, Mazumder N. One-Pot Interference-Based Colorimetric Detection of Melamine in Raw Milk via Green Tea-Modified Silver Nanostructures. ACS Omega. 2024;9(20):21879-90.

[26] Zulfiqar N, Shariatipour M, Inam F. Sustainable Fabrication of Metal-doped rGO Nanocomposites for Photocatalytic Antibiotic Degradation in Aqueous Systems. Adv Sustain. 2025;5(1):18-27.

[27] Zulfiqar N. Synthesis and Characterization of Pure and Zirconium Doped NiO-ZnO Nanocomposite for the Photodegradation of Brilliant Green Dye. SSRN 4582129. 2023.

[28] Richardson Z, Mootian G, Flannery JK, Douplik A, Laporte A, Kryshtafovych A, et al. Determining the age of spoiled milk from dried films using attenuated reflection Fourier transform infrared (ATR FT-IR) spectroscopy. Appl Spectrosc. 2019;73(9):1041-50.

[29] Alizadeh Sani M, Ehsani A, Hasani M, Ghasemi JB. Metal–organic framework fluorescence sensors for rapid and accurate detection of melamine in milk powder. Biosensors (Basel). 2023;13(1):94.

[30] Tamanna IM. Food adulteration and inadequate hygiene practices endangering public health in Bangladesh. Discov Food. 2024;4(1):109.

[31] Chu C, Li Y, Li L, Wang H, Liu J, Li H, et al. Rapid detection and quantification of melamine, urea, sucrose, water, and milk powder adulteration in pasteurized milk using Fourier transform infrared (FTIR) spectroscopy coupled with modern statistical machine learning algorithms. Heliyon. 2024;10(12).

[32] Shalileh F, Moghaddam HK, Khabbaz BF, Nahvi A, Moghaddam HK. Sensing approaches toward detection of urea adulteration in milk. Microchem J. 2023;193:108990.

[33] Silva AFS, Rocha FR. A novel approach to detect milk adulteration based on the determination of protein content by smartphone-based digital image colorimetry. Food Control. 2020;115:107299.

[34] Gonçalves IC, Fernandes GM, Rocha FR. Exploiting digital images and videos for urea determination in milk based on enzymatic hydrolysis monitoring. J Food Compos Anal. 2024;125:105745.

[35] Zulfiqar N. Exploring the World of Graphene Nanocomposites: Properties, Applications, and Progress. 2021 Jan 7.

[36] Zulfiqar N. Application of Microwaves for the Synthesis of Silver Nanoparticles via Acacia Nilotica Extract and Their Evaluation for Antimicrobial Efficacy. SSRN 4550857. 2023.

[37] Kumar N, Kumar H, Mann B, Seth R. Colorimetric determination of melamine in milk using unmodified silver nanoparticles. Spectrochim Acta A Mol Biomol Spectrosc. 2016;156:89-97.