

RECENT ADVANCES IN MILK ADULTERATION DETECTION USING SPECTROSCOPY TECHNIQUES AND MACHINE LEARNING-A REVIEW

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ABSTRACT

Across the globe, milk adulteration is a serious problem for consumers health and food quality. Common adulterants include water, starch urea, flour, and detergents. Traditional methods of detection are labor-intensive, time consuming, and inconvenience in faster assessment and field testing. This paper suggests a rapid, non-destructive, and accurate process of the detection of milk adulterants through spectroscopic procedures and machine learning (ML) models. The Spectral data obtained through the methodology of near-infrared (NIR) and ultraviolet-visible (UV-Vis) spectroscopy were preprocessed and subjected to analysis to establish the patterns of adulteration. Adulterated or pure milk samples were categorized with the help of ML models like Random Forests (RF), k-Nearest Neighbors (k-NN) and Support Vector machines (SVM). These methods enhance the detection techniques and reduce sample preparation involved in large volumes. The combination of ML and Spectroscopic methods has the potential to enhance the sensitivity and accuracy of signature based adulteration detection using spectral data analyses. The literature is structured by classifying adulterants into intentional and unintentional categories, dividing reported health effects, and assessing the advantages and disadvantages of each analytical method. This work illustrates the significance of integrating spectroscopy and machine learning for the assessment of milk quality by putting the reviewed methodologies within the broader research structure. The review describes important research gaps and future directions, such as multi-spectral data fusion, bigger and more diverse datasets, and portable systems for real-time use. This review provides a robust literature-based foundation and underscores the imperative for continued research into reliable and commercially viable milk adulteration detection systems.

KEYWORDS: Milk Adulteration, Machine Learning, Non-destructive Testing, UV-Visible Spectroscopic Methods.

1. INTRODUCTION

Raw milk (unprocessed milk), is a good source of essential nutrients such as proteins, carbohydrates, and vitamins, lipids, minerals among others [1]. The nutritional value of milk has made it a favorite commodity across the world and thus the production and supply have decreased, leading to high demand. The Basic Animal Husbandry Statistics-2024 shows that India's milk output increased by 3.78% from 2022–2023 to 2023–2024, from 230.58 million tones to 239.30 million tones. The daily amount of milk available per user has gradually grown; rising from 370 g in 2017–18 to 471 g in 2023–24. This sustained expansion underscores India's pivotal position in global dairy production and the essential requirement for maintaining milk purity and safety [2]. The imbalance between the demand and supply of milk has contributed to the unethical issue of milk adulteration [3]. Adulteration refers to degrading the quality/purity of a product. Food adulteration is the process that removes the important ingredients in natural foods, its substitution with other lower-cost food ingredients, or the introduction of adulterated or substandard or illegal food ingredients to food, generally with the intent to generate profit [4]. The most frequently used intentional adulterants of milk are water, urea, salt, sugar, and hydrogen peroxide [5]. An adulterant is urea whose main use is in increasing the content of nitrogen in the milk that is not protein based though it does occur naturally in the raw milk. It is a major contaminant that has been identified in India being in the milk and according to the Food Safety and Standards Authority of India (FSSAI), the maximum allowable percentage of its content within the sample is 70mg/dL [6]. According to reports, the amount of urea in cow and buffalo milk ranges from 18 to 100 mg/dL [7]. This study analyzed 160 milk samples from India, revealing contamination with adulterants, particularly urea. Additionally, it was observed that 4–38% of children across all age groups (n = 365) experienced headaches, while 12.5–57.3% showed signs of diarrhea. The evaluation revealed that 68.4% of milk samples from a total of 1,791 collected across 33 states exhibited urea contamination. These significant findings show that a considerable range, from about 60% to almost 100%, of raw milk samples sourced from educational canteens was affected [8]. Goat and sheep milk are more popular in stores because they have distinct properties, like being more homogeneous and less likely to create cholesterol problems. Goat milk is richer, creamier, and more nutrient-dense than cow's milk, and its smaller fat globules make it simpler to digest. This is a result of the frequent adulteration of bovine milk with goat and sheep milk [9]. The nutritional content of cow's milk is

reduced when it is diluted with water to increase its volume and financial margins. To avoid milk adulteration, it is important to regularly test milk and keep producers under supervision [10]. This study emphasizes the importance of overcoming challenges and seizing opportunities in the milk sector to achieve food security and sustainable development. Many milk adulteration detection technologies are limited to single adulterants and lack fast, cost-effective application. Thus, a reliable and accurate method for detecting common milk adulterants is essential. This review advances the subject of milk adulteration detection in a number of significant ways. In order to show how intelligent algorithms improve detection accuracy, robustness, and scalability, it first investigates the integration of spectroscopic techniques with machine learning models. A comparative methodology for assessing various spectroscopic techniques based on important factors including sensitivity, cost, and applicability for real-time applications is also provided.

2. LITERATURE SURVEY

2.1. Milk Adulterant Classification:

Milk adulterants can be categorized into two primary categories: intentional and unintentional. This classification aids in understanding the history, motive, and hazards associated with each type of adulterant shown in fig. 1.

2.1.1. Intentional Adulterants:

Water: One common way that milk is adulterated is by adding water, which can contaminate the water with bacteria, toxic chemicals, and other undesirable substances. This process increases milk output and increases profits, but it alters the composition of the milk, lowering its specific gravity, nutritional value, and visual attractiveness. According to the 2011 National Survey carried out by the Food Safety and Standards Authority of India (FSSAI), the most common adulterant in milk was polluted water, followed by detergent. The unclean water will not only lower the fat and solids-not-fat (SNF) content of the milk, but it will also dilute the milk's nutritional value and add bacteria or chemicals that could be dangerous. Adding detergent to diluted milk to make it look frothier or to keep it from going bad even more lowers the quality and safety of the milk. This emphasizes the critical need for more strict food safety laws and more reliable testing procedures, such as chemical analysis for detergents or lactometer measures for dilution [11]. The freezing point of milk is increased when water is added to it, which is a key indicator of adulteration. In accordance with its inherent composition, pure milk usually freezes at a temperature of -0.530°C to -0.550°C . By adding water, which has a freezing point of 0°C , the freezing point of milk is raised. Using exact cryoscopic measurements, the Association of Official Analytical Chemists (AOAC) approach may detect as little as 3% additional water, with a freezing point threshold of -0.550°C . When using a lactometer or other less sophisticated assays, this method is superior for detecting minute dilutions [12].

Starch, Salt and Sugar: Diabetic complications, including diarrhea, can lead to undigested starch in the intestines after consuming milk with high starch content [13]. Starch, sugar, and salt are added to modify taste, density, or lactometer reading, posing significant risks to newborns and potentially causing gastrointestinal issues [14].

Urea: Urea is commonly added to milk as an adulterant alongside water to mask the effects of dilution. Water thins the milk's texture and reduces its whiteness, but urea helps restore a denser, whiter appearance. It also serves as a preservative to prolong shelf life, increases solids-not-fat (SNF) and non-protein nitrogen levels to mimic undiluted milk's nutritional profile, lowers titratable acidity to stabilize pH, and prevents fermentation to curb spoilage. This creates the illusion of thicker, higher-quality milk, deceiving tests like the Kjeldahl method for protein content. However, urea poses health risks, including kidney strain and toxicity. Detection methods like the p-dimethylaminobenzaldehyde (DMBA) test or spectroscopy can identify urea [15]. The Food Safety and Standards Act, 2006, enforced by the Food Safety and Standards Authority of India (FSSAI), and the earlier Prevention of Food Adulteration (PFA) Rules, 1955, establish a threshold of 70 mg/100 ml for naturally occurring urea in milk. It is added to milk to boost protein and maintain thermal stability. However, excessive urea concentration can harm the kidneys, heart, and liver, potentially leading to cancer, ulcers, indigestion, and acidity [16].

Detergent: Detergents, particularly anionic detergents, are added to synthetic milk to mimic the natural properties of fresh milk, especially its creamy texture and white appearance. Synthetic milk is a fraudulent mixture made by combining water, urea, vegetable oil, neutralizers, sugar, and detergents. Water dilutes the milk, while vegetable oil replaces removed fat, and detergents emulsify this oil to create a uniform, frothy solution that resembles real milk. Urea enhances whiteness, boosts solids-not-fat (SNF) and non-protein nitrogen (NPN), stabilizes pH, and acts as a preservative. Anionic detergents are favored for their low cost and availability, effectively blending the components to deceive consumers and basic quality tests. However, detergents pose health risks, including gastrointestinal issues and potential organ toxicity. Detection methods, such as foam tests or chemical assays (e.g., with methylene blue), identify detergents, while FSSAI regulations (under the 2006 Act) prohibit such adulterants [17].

Hydrogen peroxide (H_2O_2): H_2O_2 provides the same purpose as formaldehyde, extending shelf life through preservative action. By inhibiting bacterial growth, it keeps milk from souring when refrigeration and hygiene regulations are not followed. In regions with limited access to refrigeration, hydrogen peroxide (H_2O_2) is mainly used as a preservative in milk and dairy products to activate the natural lactoperoxidase enzyme system. H_2O_2 may be present in trace levels (1–2 mg/L) in unprocessed milk as a result of chemical reactions, but ten times the concentration is required to eradicate infections. Additionally, the chemical makeup of milk may alter as a result of elevated H_2O_2 levels [18]. The use of H_2O_2 in milk preservation is prohibited for multiple reasons: it partially obscures negligence in upholding hygienic standards; it exerts a non-selective germicidal effect, disproportionately impacting lactic bacteria relative to spoilage micro flora; When used in excess for one to two days of preservation, it might give the milk unfavorable sensory qualities (such as a bitter, grating taste), even in small amounts. H_2O_2 initiates the oxidation of milk fat through the liberation of active oxygen. [19].

Vegetable Oil: A vital component in food is milk fat, affects its economics, nutritional value, and physical characteristics. It has 30% unsaturated fatty acids and 70% saturated fatty acids. Lactation, Diet, and health influence the fatty acid makeup of animals. The nutrition of dairy cows is essential. Vegetable oils can modify fat droplet composition, influencing the characteristics of dairy products. Olive oil and palm oil are frequently employed as alternatives. Cholesterol levels signify contamination with external oils. Milk fatty acids are characterized as short-chain, whilst vegetable fats are classified as long-chain [20].

2.1.2 Incidental Adulterants:

Chlorine: The milk's lower density is compensated for by adding chlorine after water, and the illness in cows also increases the milk's chlorine content [21]. Milk may be identified by conductometric sequential injection analysis, and potentiometric detection which are easy measurement procedures that may assist in diagnosing potential cardiovascular problems resulting from vascular obstruction [22].

Antibiotics: Adulteration of antibiotics can cause tissue damage, allergic reactions, antibiotic resistance, and intestinal microbiotic changes. Disruption of fermentation can lead to significant product losses and rashes [23].

Whey / liquid whey: Small doses of this medication are safe, but may cause migraines, anorexia, cramps, nausea, headaches, thirst, bloating, and increased bowel movements, potentially causing negative effects [24].

Chloride and Ammonia: Milk's chlorides change blood pH and throw off the body's acid-base equilibrium. Milk containing ammonia may result in regression, loss of acquired sensory difficulties, speech, and damage to the kidneys [25].

Formalin: It is a preservative that extends the shelf life of milk. In along with losing some of its nutrients, it is carcinogenic. The addition of sugar to milk does not significantly alter its freezing point or specific gravity, but it does decrease its pH [26].

Melamine: Melamine, a nitrogen-rich chemical, is illegally added to milk to artificially boost its protein content. It is not naturally present in milk and is used in diluted or synthetic milk, processed foods, wheat gluten, and poultry by-products. Excessive melamine can lead to serious health issues, including kidney failure and neonatal deaths. Detection relies on HPLC, mass spectrometry, or ELISA methods, as it doesn't alter milk's specific gravity, freezing point, or pH [27].

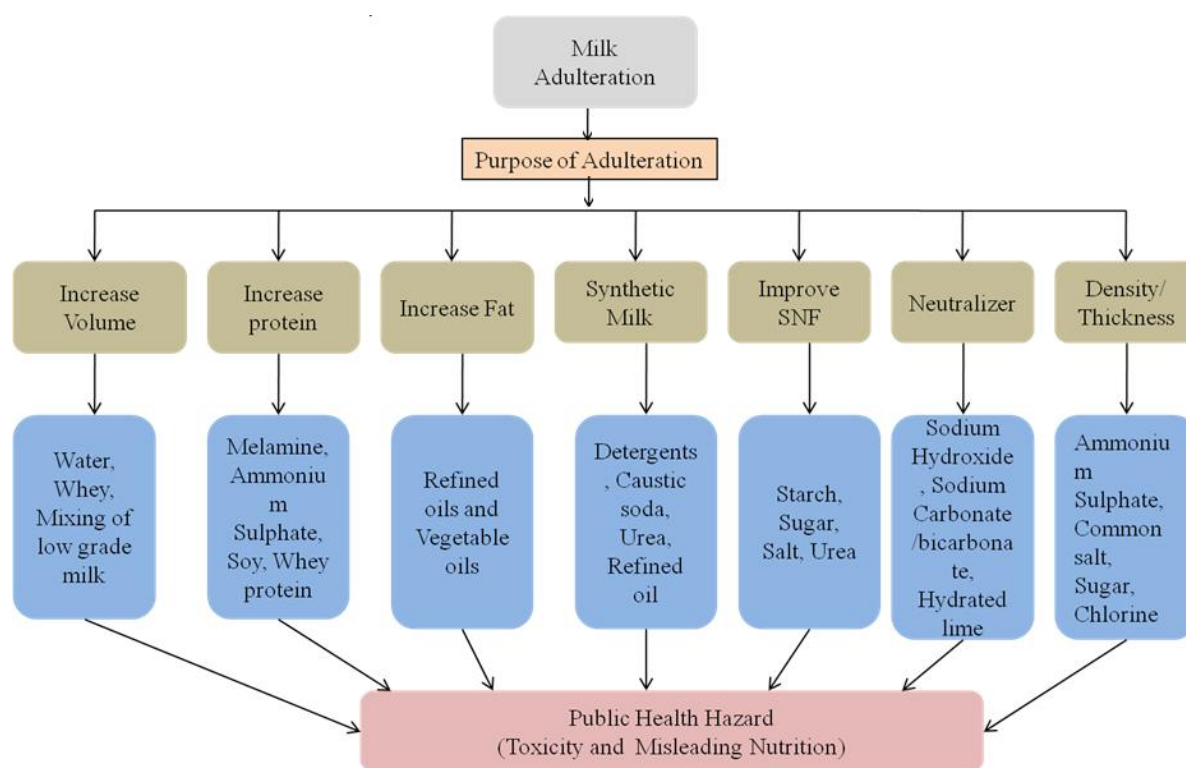


Fig. 1. Modified diagram of Classification and purpose of milk adulteration [28]

Table 1 different type of adulterants and their impacts on health

Category	Author & Year	Adulterant	Purpose/Source	Potential Health Effects
Intentional Adulterants	Ghimire S. (2016), [29]	Water	To increase volume and profits	Microbial contamination, nutrient dilution
	Barreto A. et al. (2018), [30]	Starch	To improve thickness and texture	Indigestion, harmful to infants
		Detergent	To create froth and mimic	Gastrointestinal distress,

			natural milk	toxicity
		Urea	To falsely increase protein content	Kidney damage, metabolic disturbances
		Synthetic milk	Artificial mix (detergent, urea, oil, etc.)	Highly toxic, multi-organ damage
		Sugar/Glucose	To restore taste after dilution	Risk for diabetics, obesity
		Salt	To manipulate specific gravity	Hypertension, electrolyte imbalance
		Formalin	Used as preservative	Carcinogenic, respiratory and digestive irritation
		Hydrogen peroxide	To inhibit microbial growth	Cell damage, intestinal irritation
		Vanaspati (dalda)	To simulate milk fat	Cardiovascular diseases (due to trans fats)
Incidental Adulterants	Barreto A. et al. (2018), [30]	Detergent residues	Inadequate rinsing of milk-handling equipment	GI tract irritation, long-term toxicity
		Cleaning agents	Improper cleaning of tanks or pipelines	Caustic injury to mucosa, systemic poisoning
	Bansal S. et al. (2011), [31]	Aflatoxin M1	From mold-contaminated animal feed	Hepatotoxic, carcinogenic (Group 1, IARC)
	Singh P. & Gandhi N. (2015),[32]	Heavy metals (Pb, Hg, As)	Industrial pollution, contaminated water or feed	Neurotoxicity, kidney failure, developmental abnormalities
	Sharma N. (2017),[33]	Pesticide residues	Contaminated cattle feed or water	Hormonal disruption, neurotoxicity, carcinogenicity
		Antibiotic residues	From untreated or mismanaged animal medication	Allergic reactions, antibiotic resistance

2.2. Impact of Adulteration of Milk:

Contamination is a significant issue in the global food industry, particularly prevalent in milk and various food items [34]. The degradation of the nature or quality of a substance through takes place to form adulteration [35]. Adulteration can be intentional or accidental, aiming to maximize profit by incorporating extraneous substances like water, proteins, or fats. It can also occur due to natural processes like antibiotics in milk from mastitis-treated cows or foreign contaminants during production. [36]. However, 68.7 percent of milk products do not comply, despite meeting the norms set by the Food Safety and standards Authority of India (FSSAI), with the issue being more prevalent in northern regions than in southern areas. The adulteration of food is rising in India, particularly with regard to milk, in comparison to the United States and Russia [37]. Misleading customers to secure financial gains through food, i.e. economically motivated adulteration (EMA) is also referred to as food fraud. The result of such practice may prove to be detrimental and affect the areas of public health, fair trade, and even law enforcement [38]. This paper discusses milk adulteration strategies, including dilution and deceptive substances, and policy countermeasures like spectroscopic and rapid analytical methods. It highlights practical methods for food safety, consumer protection, and ensuring milk quality in resource-constrained environments [39]. Water is an extremely often used adulterant in milk; it diminishes the nutritional value and contaminated water can lead to considerable health issues. When urea fertilizers are used excessively as a milk adulterant, the kidneys must use more effort to expel the excess urea from the body. The excessive levels of urea in the body significantly lead to various organ failures and may induce vomiting upon consumption [40]. When detergents are used as adulterants, they can be very harmful. Diarrhea is mostly caused by the excessive undigested starch present in milk [41]. They include salt and are regarded as a gradual toxin for those with heart disease and hypertension [42]. Melamine can induce renal failure and could result in death [43]. The inclusion of starch leads to diarrhea Starch-based solid milk paste may potentially induce gastrointestinal issues [44]. Milk from industrial dairies can be contaminated with sugars and adulterants to extend shelf life, whereas the unorganized industry encounters spoilage challenges due to inadequate delivery methods and the usage of hydrogen peroxide [45].

Adulterants cause diabetes people to develop life-threatening diseases. Carbonates and bicarbonates mostly cause hormonal disturbance when improperly introduced into milk. Table 1 summarises the most often reported intentional and incidental adulterants, their sources, and their impact on health.

3. Techniques for Identifying Milk Adulterants

Milk's high nutritional value makes it a vital part of the human diet, providing essential nutrients for health and growth. However, the health of consumers and food safety are at risk due to its adulteration. For many years, conventional techniques

were the standard; however, modern analytical and artificial intelligence-based technologies provide greater accuracy, speed, and sensitivity. Chemical tests and chromatographic analysis are two examples of traditional adulteration detection techniques that are accurate but frequently labor-intensive, time-consuming, and reliant on laboratory infrastructure. The focus has therefore shifted to spectroscopy-based methods, Fourier Transform Infrared (FTIR), specifically Raman spectroscopy, Ultraviolet-Visible (UV-Vis), and Near-Infrared (NIR), which enable quick, non-invasive, and reagent-free identification of chemical signatures linked to both pure and tainted milk samples [46,47]. The classification of various kinds of milk adulteration detection techniques are shown in Fig. 2. Table 2 shows that traditional approaches have problems with sensitivity, specificity, or time efficiency. This shows that we need more modern spectroscopic techniques to quickly and non-destructively find milk adulteration.

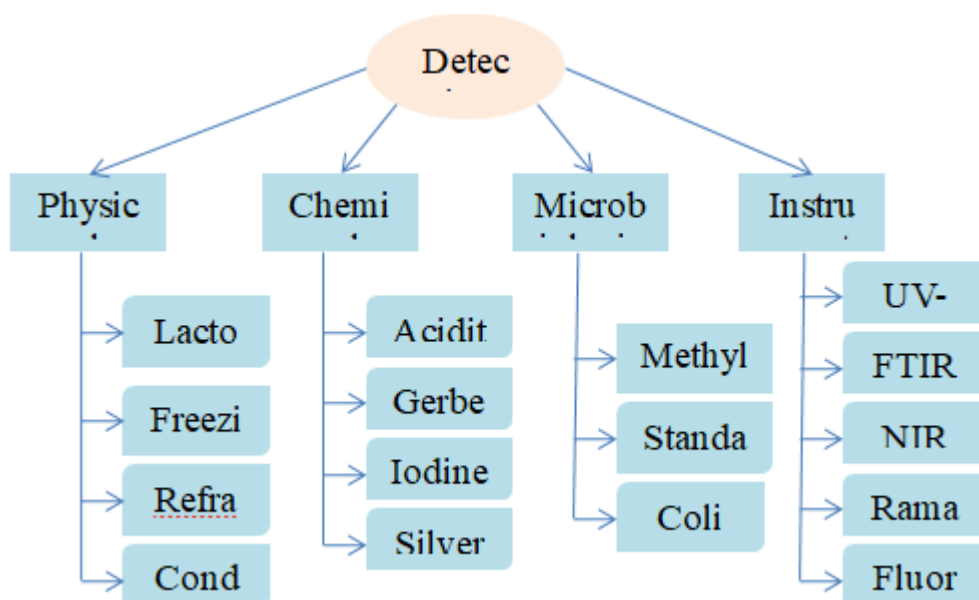


Fig. 2. Classification of milk adulteration detection techniques [48].

Table 2 Various types of milk adulteration detection techniques.

Category	Method	Detects	Principle/Technique	Limitations	Reference
Physical Methods	Lactometer Test	Water dilution	Measures specific gravity	Affected by fat/SNF content	FSSAI, 2016,[49]
	Freezing Point Test	Water, salts	Depression of freezing point	Requires precise instrumentation	Kandpal et al., 2012,[40]
	Refractometry	Solids-not-fat (SNF)	Measures refractive index	Limited to known substances	Singh & Gandhi, 2015,[32]
	Conductivity Measurement	Urea, salts	Measures ionic conductivity	Not specific to adulterants	Patel et al., 2014,[49]
Chemical Methods	Acidity Test	Neutralizers, freshness	Titration with NaOH	Time-sensitive and nonspecific	Singh & Gandhi, 2015,[32]
	Gerber Fat Test	Fat content	Sulfuric acid extraction of fat	Cannot detect water/adulterants	Kandpal et al., 2012,[40]
	Iodine Test	Starch	Starch reacts with iodine (blue color)	Only qualitative	FSSAI, 2016,[49]
	Silver Nitrate Test	Tap water	Precipitation of chloride ions	May not detect other minerals	Patel et al., 2014,[50]
	Formalin/Urea	Formalin, urea	Color change	Cannot	Singh &

	Tests		with reagent	quantify, low specificity	Gandhi, 2015,[32]
Microbiological	Methylene Blue Reduction	Microbial activity/freshness	Dye reduction by microbial metabolism	Slow, indirect measure	FSSAI, 2016,[49]
	Standard Plate Count (SPC)	Microbial load	Colony-forming unit count	Culture-dependent, takes 24–48 hrs	Kandpal et al., 2012,[40]
	Coliform Count	Hygiene indicator	Indicates fecal contamination	Requires lab setup	Singh & Gandhi, 2015,[32]

3.1. Instrumental Techniques

3.1.1 Ultraviolet-Visible Spectroscopy: The most primitive method for analysis of UV-VIS spectroscopy, which support several methods used to determine sample molar and semi-micro quantities. To get a UV-VIS spectrum, the material to be examined is exposed to electromagnetic radiation throughout a certain wavelength range. It uses monochromatic light with a single wavelength at a time. A plot of wavelength against absorption intensity is, thus, a UV spectrum. The UV and visible ranges of these spectrometers are 200–400 nm and 400–700 nm, respectively [51].

3.1.2 Near Infrared (NIR) Spectroscopy:

NIR spectroscopy, operating in the 780–2500 nm range, is widely used in dairy analysis to quantify milk components (e.g., water, fat, protein, lactose) non-destructively, offering advantages over UV-VIS spectroscopy (200–800 nm) due to its deeper penetration and ability to analyze complex matrices. Food samples are often analyzed using NIR spectroscopy during the intermediate and final product stages of the process. The main benefit of NIR is the fact it doesn't require sample preparation, which makes analysis quick and easy. Another benefit is that many components in a sample may be detected simultaneously [52].

3.1.3 Raman Spectroscopy:

Raman spectroscopy provides insights into a sample's chemical composition by analyzing light scattered through molecular interactions. It employs a laser light source to illuminate the sample, generating sufficient Raman scattered light captured by a CCD (Charge-Coupled Device) camera as a Raman spectrum. The unique fingerprint pattern in the spectrum helps identify the sample's orientation, stress, and crystallinity. This technique can detect both organic and inorganic compounds effectively [53]. This review look into chemometrics combined with Raman spectroscopy to detect and quantify adulteration in goat milk, a frequent problem due to its greater market value compared to cow milk [54].

3.1.4 Fourier Transform Infrared (FTIR) Spectroscopy:

Among infrared spectroscopy methods, FTIR spectroscopy is the most widely used technique. When infrared radiation interacts with a sample, part of it is transmitted, and part is absorbed. The detector captures a spectrum that reflects the sample's unique molecular characteristics [55].

3.1.5 Fluorescence Spectroscopy:

When a fluorescent molecule called a fluorophore absorbs UV or VIS radiation, it emits light in response. Fluorescence spectroscopy typically involves measuring two primary types of spectra to analyze sample properties: (i). An emission spectrum is generated by plotting the intensity of emitted light against the emission wavelength (λ_m) when a sample is excited at a constant wavelength (λ_x). (2). An excitation spectrum is created by scanning the excitation wavelength (λ_x) while measuring the emitted light intensity at a fixed emission wavelength (λ_m). The emission spectra at a certain λ_x are utilized in food analysis [56].

Table 3 Different kinds of milk adulteration detection techniques with their performance.

Adulterant(s) Detected	Spectroscopic Technique	ML/DL Method Used	Performance	Remarks	References
Water, detergent	UV-Vis	PCA and SVM	96.5% Accuracy	Feature extraction with classification	Das et al. (2016),[57]
Urea, starch, formalin	UV-Vis and FTIR	ANN, KNN	97-98% Accuracy	Hybrid spectroscopy-based detection	Sharma et al. (2018),[58]
Sucrose, starch	NIR	CNN	98% Accuracy	Used 1D CNN on spectral data	Pandey et al. (2020),[59]
Synthetic milk, detergent	UV and Image Analysis	XGBoost, Random Forest	95.4% Accuracy	Image with spectra fusion	Rani et al. (2022),[60]
Urea, salt, glucose	Hyperspectral Imaging	LSTM, CNN	$R^2 = 0.97$	Deep learning with HSI	Singh et al. (2023),[61]
Sodium chloride,	UV-Vis	Autoencoder with SVM	F1 Score = 0.94	Unsupervised pre-training model	Jain et al. (2024),[62]

detergent					
Water, glucose	FTIR	Decision Tree	93% Accuracy	Low-cost solution with interpretable model	Kumar et al. (2020),[63]
Hydrogen peroxide	NIR	RF and Gradient Boost	96.1% Accuracy	High classification stability	Zhang et al. (2021),[64]
Synthetic milk	UV-Vis	Naïve Bayes, SVM	91-94% Accuracy	Used reflectance-based UV input	Bansal et al. (2019),[65]
Ammonium sulfate, starch	FTIR and Raman	Ensemble Classifiers	97.8% Accuracy	Combined spectrum and boosting models	Gupta et al. (2021),[66]
Melamine, glucose	Raman Spectroscopy	CNN and LDA	$R^2 = 0.96$	2D-CNN model with supervised LDA	Li et al. (2020),[67]
Water, formalin	UV-Vis	Logistic Regression, ANN	92.5% Accuracy	ANN slightly outperformed regression	Nanda et al. (2022),[68]
Urea	Visible-NIR	SVM-RBF Kernel	95.2% Accuracy	Robust performance with nonlinear kernel	Prasad et al. (2018),[69]
Starch, glucose, formalin	NIR and UV	Random Forest, CNN	>95% Accuracy	Multi-class detection model	Tiwari et al. (2021),[70]
Urea, detergent	FTIR	LightGBM	97% Accuracy	Lightweight gradient boosting classifier	Meena et al. (2023),[71]
Formalin, salt	NIR	kNN and Decision Trees	93% Accuracy	Low-complexity classifiers on preprocessed data	Wong et al. (2022),[70]
Hydrogen peroxide	UV-Vis	LDA, ANN	94.5% Accuracy	LDA used for dimensionality reduction	Roy et al. (2019),[72]
Melamine	FTIR	SVM, CNN	AUC = 0.98	Deep CNN yielded best performance	Ahmad et al. (2020),[73]
Water, detergents	Raman and UV	ResNet-50 Transfer Learning	97.6% Accuracy	Transfer learning with pre-trained CNN	Akbar et al. (2021),[74]
Mixed adulterants	FTIR and UV	Ensemble CNNs	>96% Accuracy	End-to-end deep learning pipeline	Iqbal et al. (2022),[75]

The current research illustrates considerable advancements in the detection of milk adulteration by the integration of spectroscopic techniques and machine learning algorithms. Many studies have shown that it is possible to find both intentional and unintentional adulterants, which shows how dangerous they may be to health and how important it is to have quick detection tools. Spectroscopic techniques, including UV-Visible, FTIR, and Near-Infrared spectroscopy, have demonstrated significant potential owing to their non-destructive characteristics and capacity to provide compositional data. Concurrently, machine learning models have improved the precision and interpretability of spectrum information. Table 3 highlights that near-infrared (NIR), Fourier-transform infrared (FTIR), and Raman spectroscopy combined with advanced ML/DL algorithms demonstrate superior performance compared to conventional detection methods.

4. CHALLENGES AND FUTURE SCOPE

Spectroscopy struggles with the complex composition of milk, overlapping spectral signals, and low sensitivity to trace adulterants [76]. High instrument costs, calibration needs, and inconsistent sample preparation further limit its practical use [77]. Accurately interpreting spectrum data requires complex data processing and chemometric techniques due to its complexity, which can be computationally demanding and call for particular expertise [78]. ML requires large, labeled datasets and effective feature extraction, which are often lacking [79]. Models may overfit or fail to generalize across milk types, and results depend heavily on data quality and diversity. DL models need vast data, are computationally intensive, and difficult to interpret [80].

Although spectroscopy, ML and DL individually has their own limitations, including interpreting needs, data dependency, and spectrum complexity, their combination provides a potent remedy. DL improves accuracy through deep feature learning; ML assists in extracting significant patterns; and spectroscopy offers abundant, non-destructive chemical data. When combined, these techniques can overcome the flaws of each one alone, allowing for the quick, precise, and economical detection of many milk adulterants even at trace levels which makes them perfect for portable, real-time testing devices.

5. CONCLUSION

Milk adulteration continues to pose a serious and evolving threat to food safety and public health, often involving harmful substances that are difficult to detect using conventional methods. Although various analytical techniques exist, many are hindered by high costs, complex procedures, and lack of suitability for rapid or field-based testing. This review emphasizes the potential of spectroscopic methods, including NIR, MIR, Raman, and UV-Visible spectroscopy, for rapid, non-destructive milk analysis. When combined with advanced data analysis tools such as machine learning (ML) and deep learning (DL), spectroscopic techniques significantly enhance the accuracy of identifying trace adulterants in milk.

To maximize the effectiveness of spectroscopy-based detection, future initiatives should focus on enhancing the quality of spectral data, streamlining equipment design, and developing uniform testing standards. Special attention should be given to developing affordable, portable, and easy-to-use tools that can be deployed in rural and field settings. Advancing these technologies will support early detection of adulterants, minimize fraudulent practices, and ultimately ensure the delivery of safe, high-quality milk to consumers worldwide.

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