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Organic Milk beyond Certification: From Production-System Variability to Analytical Authentication and Industrial Quality

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ABSTRACT

Organic milk occupies a distinctive position in the dairy industry because of the assurances that certification provides. These assurances link production to organic feed and minimal synthetic inputs, and certification also sets standards for pasture or outside access, animal-welfare measures, verified traceability and more. However, certification does not guarantee that a sample has a better composition, lower levels of contaminants, or a distinctive analytical fingerprint. This critical narrative analysis examines peer-reviewed data on organic milk from 2020 to 2025, including the production system, dairy chemistry, nutritional quality, microbiological and chemical safety, authenticity testing and industrial usage. The research shows that systems rich in pasture generate higher n-3 fatty acids and conjugated linoleic acid, whereas gross fat, protein, lactose, minerals, vitamins, sensory qualities, microbial ecology, somatic cell count and residue occurrence remain strongly dependent on season, breed, lactation, location, feed quality, cleanliness, processing and storage. Thus, organic milk should not be automatically preferred over ordinary milk. The most defensible verification depends on a combination of orthogonal measures (fatty acid profiling, stable isotope ratio, FTIR/MIR/NIR spectroscopy, chromatography, nuclear magnetic resonance, residue screening and chemometric or machine learning classification) and certification records. Rapid spectral devices are expected to be utilized for regular screening. They must, however, be externally validated, transferred to instruments, shown to be seasonally resistant and tested using blind samples and a confirmatory reference technique before they can be used in industry. The review proposes a joint quality and authenticity approach for premium fluid milk, fermented products, cheese, butter, milk powders, functional foods and digitally traceable supply chains. Future research should prioritize multicountry reference databases, uniform sampling, uncertainty reporting, model explainability and validation against authorized laboratory procedures.

KEYWORDS: Organic milk; fatty acids; milk quality; residues; FTIR; stable isotopes; chemometrics

1. INTRODUCTION

The farming method and certification integrity – not a single chemical composition – are what constitute organic milk. Rules concerning feed origin, veterinary medications, land management, outdoor access, record-keeping and separation from non-organic materials are usually listed in organic standards. Therefore, the commercial claim is based on process, while the product given to the customer is evaluated according to composition, safety, sensory quality and authenticity. This is an important differentiation: certification may indicate that specified processes took place, but it does not in itself provide a specified nutritional profile or guarantee absence of all contaminants. Recent evidence suggests that it cannot be simply claimed that organic milk is better than conventional milk (Linehan *et al.,* 2024; Kononets *et al.,* 2023; Knorr, 2023; Calabrò & Vieri, 2023). In fact, recent evidence suggests that the quality and composition can be affected by many interacting determinants such as fodder intake, availability to pasture, breed, stage of lactation, season, farm intensity, soil conditions, local climate and the processing history. These determinants will give rise to a certain degree of overlap in compositional characteristics in organic and conventional products. In some cases, this overlap can be greater perhaps than the impact of certification category itself. Hence, validity of assessment is key to emerging claims, which must disentangle system-

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level trends from universal product claims (Manuelian *et al.,* 2022; Kasapidou *et al.,* 2023; Tzamaloukas *et al.,* 2021; Ormston *et al.,* 2023).

Premiums in the market can lead to incentives for changing the use of the product, dilution, fraudulent claims of origin, misappropriation of organic labels and the like. Confusion can arise when consumers expect labels to reflect reality, but the evidence analyzed does not support this. Moreover, a supply-chain disclosure choice may impact trust regardless of the inherent quality of the product itself. Therefore, research on organic milk increasingly intersects with food fraud detection, information economics, sustainability assessment, and consumer behavior areas (Dinçer *et al.,* 2023; Momtaz *et al.,* 2023; Sadiq *et al.,* 2020; Yu & He, 2021).

This review applies that analytical framework to synthesize the published evidence. The goals are to (i) identify the production and management drivers of organic milk characteristics (ii) synthesize evidence on composition, nutritional properties, microbiological quality and chemical safety (iii) critically analyze authentication technologies (iv) relate the laboratory evidence to the industrial application (v) identify gaps in methodology which prevent universal qualification or health claims. This paper will include only validated peer-reviewed literature from 2020-2025 and conclusions that are appropriate to the evidence (Manuelian *et al.,* 2020; Gamage *et al.,* 2023; Giampieri *et al.,* 2022; Formaggioni & Franceschi, 2024).

2. REVIEW METHODOLOGY

Instead of using a conventional systematic review or meta-analysis, we employed a structured critical narrative. The search concepts included organic milk, conventional milk, dairy composition, fatty acids, minerals, microbiome, somatic cell count, about mastitis, residues, aflatoxin M1, pesticides, heavy metals, spectroscopy, stable isotopes, and machine learning, food fraud, traceability, and industrial dairy applications. The scope comprised peer-reviewed journal publications published between January 2020 to December 2025. Research that reported on the direct comparison trials, current reviews, method-development publications, and findings with clear dairy relevance was prioritized (Ceniti *et al.,* 2023; Grassi *et al.,* 2023; Julmohammad *et al.,* 2025; Linehan *et al.,* 2024; Xu *et al.,* 2025).

Research that had at least one of five domains: production-system context, chemical or nutritional content, microbiological or contaminant quality, analytical authentication or industrial implementation was included. Anything not related to milk or dairy was excluded from the main synthesis if it had no discernible analytical basis, or if it simply repeated claims with no primary or review evidence. Due to the heterogeneity in design, matrices, units, seasons and analytical platforms, meaningful pooled estimates were not possible and so this evaluation was focused on direction, consistency, modifiers and translational significance rather than numerical aggregation (Katerinopoulou *et al.,* 2020; Martin *et al.,* 2023; Varzakas, 2023).

Bibliographic metadata and DOI strings were compared to the records in the publisher sites, DOI records or indexation information for the article. The final reference list has 90 distinct journal references with DOI, 2020–2025. This technique does not replace journal-specific systematic review standards and protocols registration, duplicate screening and formal risk-of-bias assessment, but does enhance evidence-base traceability (Chung *et al.,* 2022; Mendes & Duarte, 2021).

Table 1. Scope and eligibility framework used for the critical narrative review

Element	Operational definition	Review decision
Publication window	January 2020–December 2025	Retained only current journal literature within the defined period
Evidence types	Comparative studies, analytical-method papers, systematic or critical reviews, meta-analyses	Used according to the question addressed; no inappropriate pooling
Core domains	Production, chemistry, quality/safety, authentication, industrial application	At least one domain required for inclusion
Verification	Persistent DOI checked against publisher or indexed metadata	90 unique DOI-linked references retained
Synthesis method	Critical narrative comparison of direction, modifiers, limitations, and utility	No PRISMA counts, meta-analysis, or invented effect sizes

3. ORGANIC DAIRY PRODUCTION SYSTEMS AND THE BASIS OF THE CLAIM

3.1 Production intensity, feed, and farm structure

The organic category is quite diverse internally; the systems vary in terms of input levels from high-input confinement to wide grazing. This may be affected by specific circumstances such as farm size, bought feed, forage quality, milk output, breed, availability of land and regional infrastructure. This can affect environmental performance as well as the composition of milk. Organic dairy production may reduce dependence on certain external input commodities and may improve chosen metrics of environmental impact, but not necessarily perform better than conventional. If system boundaries are poorly defined, gains may be outweighed by decreased yield or land-use implications. The practical adoption of organic farming may be influenced by the level of knowledge about organic farming, the costs of certification, access to markets, perceived risk, availability of labor, price premiums and institutional support. These adoption limits might explain unequal geographical

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distribution of certified organic milk supply and heterogeneity in management intensity. Sustainability promises need to be taken seriously at the farm and supply-chain level – not taken at face value from a label (Sapbamrer & Thammachai, 2021; Gamage *et al.,* 2023; Calabrò & Vieri, 2023; Manuelian *et al.,* 2020).

3.2 Animal welfare & outdoor access

Organic guidelines usually include access to the outdoors, pasture, adequate stocking density and preventative health care methods. But real welfare results are dependent on execution, climate, housing design, lameness management and feeding as well as veterinary treatment. Systematic mapping suggests greater chances for behavior in organic systems, but no production label ensures higher wellbeing across all metrics (Smid *et al.,* 2020; Wagner *et al.,* 2021; Åkerfeldt *et al.,* 2021).

Access to the outdoors may influence behavior, mobility and exposure to weather and other environmental elements. These factors may indirectly impact milk via such things as feed selection, energy balance, heat load and cleanliness. The pertinent scientific issue is not whether outdoor access is desirable in all situations, but how the design and management utilized interact with animal demands and local limits (Smid *et al.,* 2020; Ormston *et al.,* 2023).

3.3 Certification, traceability and customer awareness

Certification is an auditable claim on a complex manufacturing process. Records of chain of custody, separation of collection, and recorded input authenticate evidence. The current trend in organic certification is towards digital documentation and risk-based management, but an analysis that checks identification would complement certification, not replaces it (Knorr, 2023; Kononets *et al.,* 2023; Yu and He, 2021).

For Americans, the phrase “organic” is often associated with health advantages for the product, environmental performance, animal welfare, purity and localness. These features do not always co-occur. Clarity of communication is therefore important so that process claim is not incorrectly understood to be medical claim or promise of zero residues (Dinçer *et al.,* 2023).

4. CHEMICAL COMPOSITION AND NUTRITIONAL CHARACTERISTICS OF ORGANIC MILK

4.1 Ingredients composition and characteristics

The major factors affecting the nutritional density and processing output of milk are fat, protein, lactose, ash, total solids and water. Nevertheless, there is a lot of overlap between organic and regular milk. Breed, calorie intake, stage of lactation, season, milk yield and sample design impact fat and protein. Thus, investigations that reveal small group differences should be understood in a context-specific way rather than as diagnostic thresholds of biological identity (Brodziak *et al.,* 2021; Kasapidou *et al.,* 2023; Manuelian *et al.,* 2022; Linehan *et al.,* 2024).

Even little variations in composition may impact yield, coagulation, fermentation, heat stability, powder behavior and standardization for cheese. Milk for processing, whether organic or not, needs to work the same as ordinary milk. Processors generally need standardisation of fat to protein ratio and solids independent of manufacturing technique (Brodziak *et al.,* 2021; Martin *et al.,* 2023; Formaggioni & Franceschi, 2024).

4.2 Fatty acid composition - the most common composition signal

The fatty-acid fraction provides the most convincing evidence for system-related differentiation. Diets that are high in forage and pasture increase the levels of alpha-linolenic acid (ALA), total n-3 fatty acids and rumenic acid and reduce the n-6:n-3 ratio. The trends are linked to rumen biohydrogenation, fodder lipid content and animal metabolism. Organic systems use more fodder, although this is driven by diet more than certification (Davis *et al.,* 2020; Liu *et al.,* 2020; Ormston *et al.,* 2023; Poulsen *et al.,* 2020).

Season is an important modulator as the availability of fresh herbage; the utilization of stored forages and energy supplements vary throughout the year. Breed and genotype affect synthesis and unsaturation of fatty acids. Therefore, an organic sample in winter on conserved feed may be more comparable to a sample of conventional pasture than to another organic sample in summer (Poulsen *et al.,* 2020; Tzamaloukas *et al.,* 2021; Kasapidou *et al.,* 2023; Manzocchi *et al.,* 2021).

Conjugated linoleic acid is often employed as a functional additive, although biological interpretation must be done with care. Increasing CLA in milk does not have a clinically relevant impact at usual consumption and various CLA isomers have varying effects. Functional proof reviews propose the lipid fraction of interest; they also focus on dosage, matrix and safety (Gebereyowhans, 2024; Badawy *et al.,* 2023; Martini *et al.,* 2023).

4.3 Minerals, Micronutrients, Sterols and Bioactives

The mineral concentrations in milk are a reflection of the mineral supply of the animal’s diet, the mineral composition of soils and forages, water, stage of lactation, season of the year, and analytical procedures. Studies that have compared both plants and cattle have identified a variety of macro and trace elements to be different but the nutritional importance

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will be smaller than the difference proved to be statistically significant. Organic state alone is a poor predictor of mineral density (Stergiadis *et al.,* 2021; Qin *et al.,* 2021; Cimmino *et al.,* 2023).

Milk contains bioactive compounds such as tocopherols, sterols, phospholipids, peptides etc. These components may contribute to the product distinctiveness and functional food. However, they are particularly sensitive to heat treatment, fermentation, storage, fat content and analytical definition. The proofs must distinguish between compositional existence vs health consequences as demonstrated (Lin *et al.,* 2021; Singh *et al.,* 2023; Martini *et al.,* 2023).

4.4 Interpretation on human health linked

Research has shown dairy products are a source of calcium, protein, phosphorus, vitamin B_{12} and riboflavin. Dairy items are often assessed as a whole in systematic reviews and trials, not certified organic milk as a distinct intervention. Therefore, it is improper to extend dairy-health findings to a blanket statement that organic milk prevents illness (Wallace *et al.,* 2021; Rizzoli, 2022; Hidayat *et al.,* 2023).

The evidence for cancer is complex too. In contrast, preventative guidelines consider dietary patterns, body composition and physical activity. Large observational and mendelian-randomization studies evaluate milk intake. They found no evidence that organic milk alone might cause or prevent cancer. Health communication has to be limited to information on validated composition/authorized nutrition claims (Lumsden *et al.,* 2023; Clinton *et al.,* 2020).

Table 2. Evidence synthesis for organic versus conventional milk attributes

Attribute	Recurrent evidence pattern	Major modifiers	Critical interpretation
Gross composition	Small or inconsistent differences in fat, protein, lactose, solids, and ash	Breed, lactation, yield, season, sampling, standardization	Not suitable as a stand-alone authenticity marker
n-3 fatty acids and CLA	Often higher under forage-rich or pasture-based organic systems	Fresh herbage, conserved forage, concentrate level, season, genetics	Most reproducible tendency, but driven primarily by feeding system
Minerals and micronutrients	Differences reported for selected elements and bioactives	Soil, feed, water, season, analytical method	Statistical differences may have limited nutritional magnitude
Microbiological quality	No guaranteed organic advantage; wide farm-to-farm variation	Milking hygiene, mastitis, cooling, storage, processing	Certification does not replace hygiene control
Residues and contaminants	Organic rules may reduce some exposure pathways but cannot ensure zero occurrence	Feed contamination, environmental drift, cross-contact, veterinary use	Requires routine screening and confirmatory analysis
Sensory and processing behavior	Can differ with forage and processing history	Diet, fat composition, heat treatment, fermentation, storage	Product-specific validation is required

5. MICROBIAL ECOLOGY, UDDER HEALTH, AND SENSORY QUALITY

5.1 Milk microbiome and farm environment

Several factors may affect the actual composition of the microbiota of testing milk in the laboratory. The microbial community structure shows differences in organic and conventional farms but it is difficult to assign causality since the farm environment and management co-vary with production method. Microbiome studies are also exposed to minor biomass contamination as well as to live cells or DNA being evaluated (Berg *et al.,* 2020; Van De Grift *et al.,* 2025; Gomes *et al.,* 2020).

Safety and technical adequacy are not linked to microbial diversity. Lactic acid bacteria as well as spoilage organisms and pathogens are present in raw milk. In order to make a choice of probiotic or starter cultures, farm label is not sufficient; strain level characterization, safety assessment, technical performance and stability should be done (Reuben *et al.,* 2020; Sabunevica and Zagorska, 2023; Murali *et al.,* 2023).

5.2 Somatic, mastitis and processing quality cell count

The somatic cell count is a realistic measure of udder inflammation. Furthermore, it has been associated with alterations in enzyme activities, proteins, lipolysis and poor processing quality. It may be possible to assess immune cell populations with the help of differential somatic cell count and easier ways of checking more often. While organic and conventional herds differ in their management practices, preventing and detecting mastitis early is a concern for both systems (Stocco et al., 2020; Deng et al., 2020; Neculai-Valeanu & Ariton, 2022; Fonseca *et al.,* 2025).

Elevated counts of somatic cells may influence the quantity and the quality of cheese and are likely involved in microbial. Managing mastitis effectively remains necessary, but while organic constraints may limit option choices of the therapeutic routes. The proper comparison, therefore, is herd level udder health management and not the assumption of intrinsic superiority (Moradi *et al.,* 2021).

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5.3 The sensory qualities and identity of a product

Feeding fresh herbage, hay or silage can alter the scent, colour, texture and flavour of the milk due to changes in volatile chemicals, carotenoids and fatty acids. The variations in taste and texture may justify a premium price, but whether it is acceptable depends on the market. For this reason, sensory authenticity should be checked using panel or instrumental correlation verification, not label expectation verification (Manzocchi *et al.,* 2021; Brodziak *et al.,* 2021; Formaggioni and Franceschi, 2024).

6. SAFETY REGARDING CHEMICAL AND MICROBIOLOGICAL ELEMENTS

6.1 Hygiene and management of raw milk and processing

The quality of raw milk is determined by its initial microbial load, development of psychotropic bacteria, type of spore-forming bacteria, the speed and temperature of cooling water, storage time, cleanliness of tanker and quality of milk processing. The recent evaluation of raw milk quality calls for expanding the definition of raw commodity quality that links farm and downstream product performance. Biofilm persistence, inadequate cleaning, and delayed cooling can't be resolved by organic certification (Wang *et al.,* 2021; Fusco *et al.,* 2020; Martin *et al.,* 2023).

According to complicated dairy value chains, the absence of cold chains, poor handling and insufficient testing may lead to serious safety issues, regardless of production philosophy. In markets with ineffectual certifications and lab capabilities, as well as organic claims, these findings are particularly pertinent.

6.2 Residues of antibiotics

Under organic rules veterinary pharmaceuticals may not be allowed or may be limited but animal welfare demands that treatment be given when clinically indicated. Residues can occur due to non-compliance, insufficient time for withdrawing product, cross-contamination or record failures. According to systematic data, routine screening of all milk streams is still necessary, and positive or doubtful results are checked using approved methods (de Freitas *et al.,* 2021; Teixeira *et al.,* 2020; Costa *et al.,* 2024).

Vibrational spectroscopy with machine learning is a promising way for quick screening of residues, but its performance at regulatory levels may be hampered by matrix effects, detection limit and calibration transfer. Confirmatory chromatography-mass spectrometry still required in enforcement judgments (De Freitas *et al.,* 2021; Ashraf *et al.,* 2024).

6.3 Heavy metals and pesticides

Contaminated feed, pasture, water, environmental deposition, and indirect exposure to pesticides may all result in milk contamination. While organic growing reduces the permissible use of many synthetic pesticides and fungicides, it cannot prevent drift, legacy contamination, or cross-contact in the supply chain. With that, global studies tend to opt for risk-based monitoring instead of zero residues (Boudebbouz *et al.,* 2022; Verdini & Pecorelli, 2022).

Soil, feed, water, industrial emissions, equipment, and local geology all contribute to heavy metal contamination. In general, their incidence poses an environmental and feed safety concern, rather than simply an organic certification characteristic. Using established methodologies, detection limits of appropriate value and geographically representative sample (Ashraf *et al.,* 2024; Boudebbouz *et al.,* 2021).

The breakdown of aflatoxin B1 from the dairy cow diet generates aflatoxin M1. Carryover depends on intake, milk production, animal metabolism, and feed contamination. Thus, climate, storage humidity, and management of feed materials are important variables. Organic feed might also be subject to fungal development (Turna & Wu, 2021; Min *et al.,* 2021).

According to findings and summary assessments, fair regional variation and ongoing observation, especially in meteorological regions and unregulated supply chains, are crucial concerns. Biosensors may ease the screening, but confirmatory analysis and quantitative validation in the milk matrix is still required (Jahromi *et al.,* 2025; Narjabadi Fam and Massoud, 2023; Malissiova *et al.,* 2024).

7. METHODS FOR VERIFYING AUTHENTICITY OF ORGANIC MILK

7.1 No one marker is sufficient

It is difficult to authenticate organic milk because we are after a manufacturing method, not a molecule. The effect of diet and location on fatty acids, isotopes, metabolites, minerals and spectra, is in the study. A robust method uses documentary traceability and uses at least two analytical domains, with categorization undertaken only within a well-chosen reference population.

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7.2 Profiles of fatty acids and compositions

Fatty acid gas chromatography provides interpretable indicators of forage and concentrates intakes. The chemometric model is able to discriminate between production systems at geographic locations based on mixtures of n-3 fatty acids, CLA, branched-chain fatty acids and other lipids. It is expensive and hard to prepare a sample that does not drift seasonally. Furthermore, feeding habits will converge between certification types. The predicted values of fatty acids by infrared may reduce the analytical cost and may increase the analytical throughput. However, the predicted values have limitations associated with the calibration set. Machine-learning methods may improve predictions of targeted fatty acids. However, prediction validations in different breeds, devices, and seasons should be done independently (Zhao *et al.,* 2023; Mendes & Duarte, 2021).

7.3 FTIR, MIR, NIR and portable spectrometers

Spectroscopies in the mid-infrared range and Fourier-transform infrared are timesaving and non-destructive, and they can fit any conventional dairy lab. Through the multivariate analysis of the data, it may be possible to identify dilution, urea, sucrose, milk powder, species replacement and other types of adulteration (Ceniti *et al.,* 2023; Balan *et al.,* 2020; Tan *et al.,* 2023; Chu *et al.,* 2024).

Data obtained from buffalo, goat, camel, horse, sheep, and A1/A2 milk have shown that very small spectral alterations allow for classification when the models are matrix-specific, which is a wider concept. These applications are analytically important to organic cow milk in that they illustrate how species, composition and processing impacts may be separated – or confused – in the same spectral space. The screening will now be more closely positioned to receiving ports and the field location. It is possible that portable deployment can hasten firm choices while simultaneously limiting the spectrum, equipment variations and temperature sensitivity along with model maintenance. So confirmatory paths become much needed (Liang *et al.,* 2025; Gullifa *et al.,* 2025; Xu *et al.,* 2025).

7.4 Analysis of ratios of isotopes

The stable isotopes of carbon, nitrogen, hydrogen and oxygen can give information on feed type, water supply, climate and geography. Carbon isotopes can distinguish between feed supplies from C3 and C4 plants, while hydrogen and oxygen isotopes reflect water supplies and other geographical conditions. Isotope evidence becomes robust with connection to references of seasonal and regional levels (O'Sullivan *et al.,* 2023; Hamzić Gregorčič *et al.,* 2020).

The frameworks of stable isotopes can also be used for the identification of surplus nitrogen or reconstituted milk powder and chemometrics. Nonetheless, various diet supply and isotopic overlap make universal cut-offs impossible. The strategy is best understood probabilistically and in conjunction with records, fatty acids, and spectra (Jin *et al.,* 2022; O'Sullivan *et al.,* 2023).

7.5 Chromatography, NMR and confirmation by targeted techniques

Specialist areas of work at the laboratory have ion chromatography, liquid chromatography, gas chromatography etc. Nuclear magnetic resonance can also analyze dairy fats and provide compositional fingerprints containing saponification-related data. These platforms are fairly specific but nevertheless require specialist staff and quality assurance and are more costly than conventional spectrum screening (Ashraf *et al.,* 2024; Ivanova *et al.,* 2022; Verdini and Pecorelli, 2022). Testing for authenticity is not just restricted to the testing of fluid milk but also to the milk fat. The detection of coconut oil or hydrogenated vegetable oil in dairy fat using ATR-FTIR and chemometrics: the role of matrix specific models for premium organic butter and ghee (Gandhi *et al.,* 2022; Sonvanshi *et al.,* 2024).

7.6 Chemometrics and machine learning

Chemometrics is the science in which one uses mathematical and statistical methods to analytical data, usually of high dimensionality, to extract predictive, exploratory or classification information. Principal component analysis can help visualize the data. Supervised techniques such as partial least squares discriminant analysis, random forests, support-vector machines, logistic regression, deep learning must have pre-set validations, class balance, and defense against data leakage (Grassi *et al.,* 2023; Chung *et al.,* 2022; Varzakas, 2023).

8. INTEGRATED QUALITY AND AUTHENTICATION WORKFLOW

An effective organic milk control system should connect farm documentation, sample integrity, rapid chemistry, safety testing, multivariate authentication, and release decisions. The workflow begins with certified supplier approval and batch-level traceability, followed by representative sampling under controlled temperature. Routine composition, acidity, somatic cell count, microbial indicators, and residue screens establish quality and safety. Spectral and isotope methods then provide authenticity evidence, while chemometric models compare the sample with a validated reference domain (Martin *et al.,* 2023; Costa *et al.,* 2024; Hou *et al.,* 2023; O'Sullivan *et al.,* 2023).

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Table 3. Comparative appraisal of major authentication technologies

Technology	Primary information	Strengths	Key limitations	Best industrial role
Fatty-acid GC	Diet- and metabolism-related lipid profile	Interpretable; strong forage signal	Cost, derivatization, seasonal overlap	Reference profiling and model calibration
FTIR/MIR	Whole-sample molecular fingerprint	Rapid, non-destructive, high throughput	Instrument and temperature effects; model transfer	Routine receiving-dock screening
NIR/MicroNIR	Portable compositional and adulteration fingerprint	Field-ready and fast	Lower specificity; narrower range	On-site triage and batch screening
Stable isotopes	Feed, water, geography, reconstitution signals	Orthogonal to routine composition	Requires matched reference databases	Origin verification and dispute resolution
LC/GC-MS/MS	Residues, contaminants, targeted analytes	High sensitivity and specificity	Expensive; skilled laboratory required	Regulatory confirmation
NMR/metabolomics	Broad lipid/metabolite fingerprints	Rich structural information	Cost and standardization challenges	Research databases and high-value products
Chemometrics/ML	Integration of multivariate evidence	Scalable classification and anomaly detection	Overfitting, drift, opaque decisions	Decision support with external validation

A sample should not be declared authentic solely because a classifier assigns a high probability. The decision must consider certificate status, chain-of-custody integrity, model applicability, analytical uncertainty, and whether confirmatory testing is required. This governance layer is essential for auditability and for managing false-positive and false-negative costs (Varzakas, 2023; Kononets *et al.,* 2023; Yu & He, 2021).

9. INDUSTRIAL APPLICATIONS

9.1 Premium fluid milk and extended-shelf-life products

Premium organic fluid milk relies on label integrity, a consistent sensory quality, a standardized composition and a strong cold chain. Rapid infrared screening can effectively aid with intake decisions while residue and microbiological testing mitigate risk. In addition to requiring heat stability due to extended shelf life and UHT processing, the spectral fingerprint can also be affected, resulting in a misalignment of the models (Brodziak *et al.,* 2021; Martin *et al.,* 2023; Tan *et al.,* 2023).

9.2 Fermented Items and Probiotic Dairy Products

Yogurt, kefir, cultured milk, and probiotic drinks require predictable protein functionality, lactose availability, starter culture compatibility, and low contamination pressure. Organic milk may support differentiated products, but the fermentation performance is more directly dependent on the heat treatment, solids standardization, starter strain, inhibitory residues and process control than the label (Sabunevica and Zagorska 2023; Reuben *et al.,* 2020; Murali *et al.,* 2023).

9.3 Cheese, Butter, Ghee and Cream

The yield and texture of cheese is sensitive to casein, fat, calcium balance, somatic cell count and proteolytic activity. Butter and ghee have a profile that is concentrated in fat which leave them open to substitution with cheaper oils due to economic reasons. Supplier records should be validated with a combination of chromatographic verification (Moradi *et al.,* 2021; Gandhi *et al.,* 2022; Sonvanshi *et al.,* 2024; Martini *et al.,* 2023).

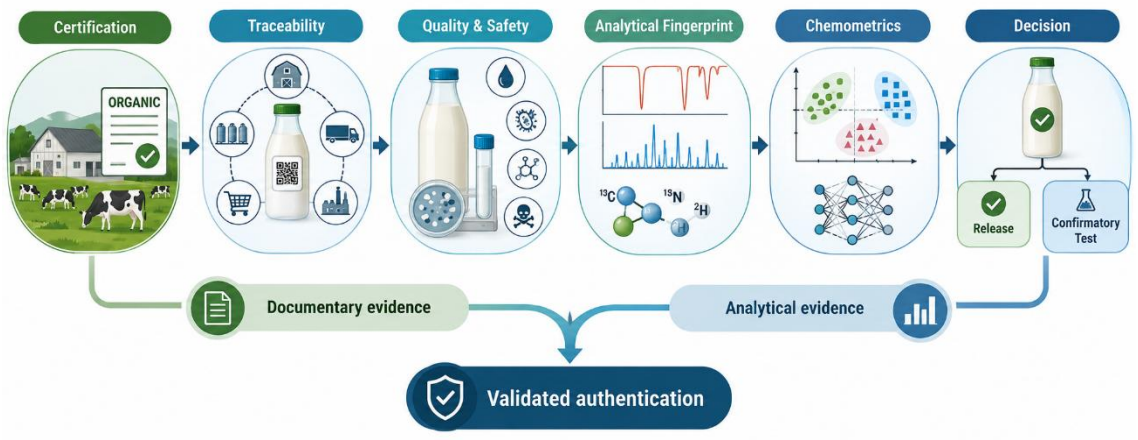


Figure 1. Integrated Quality Assurance and Authentication Workflow for Organic Milk

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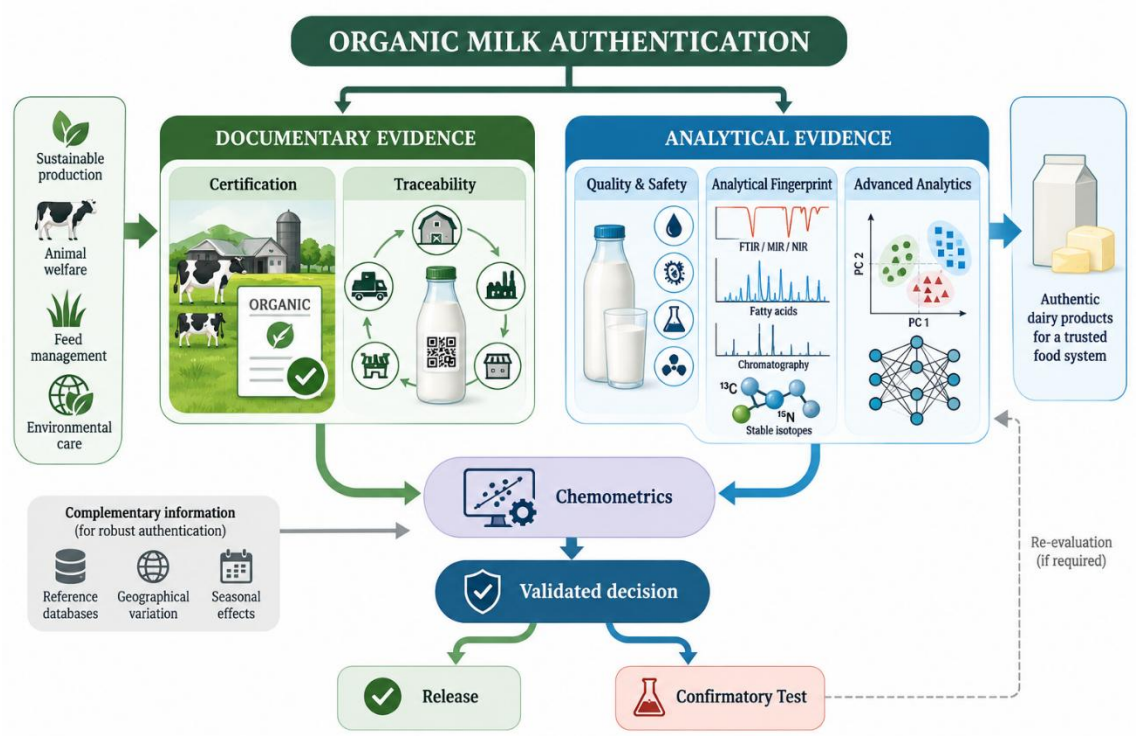


Figure 2. Integrated Evidence Framework for Robust Authentication of Organic Milk

9.4 Milk powders, ingredients of infant foods and functional products

In the case of Infant-food ingredients and Milk powders, aflatoxin M1, residues, oxidation, microbiological quality, reconstitution status and traceability must be strictly controlled. Products that are to claim to contain omega-3, CLA, peptides or micronutrients and which are sold on the basis of these constituents need to have analytical proof of the constituent claimed as well as stability during processing and shelf life. Research conducted by Jin *et al.,* 2022 examines a significant gap in the continuity literature.

9.5 A high-value export market therefore requires it

More auditable organic claims can be facilitated by digital batch certificates, supplier-risk profiles, spectral libraries, and more linked lab results. The aim is not to replace inspectors with algorithms, rather to link documents and analytical evidence so that anomalies trigger proportionate investigations. Systems that provide visibility along the supply chain are particularly beneficial in various fragmented supply chains and export markets characterized by high costs of fraud (Kononets *et al.,* 2023; Yu & He, 2021; Knorr, 2023).

Table 4. Industrial applications and associated control priorities

Product/application	Critical quality controls	Authentication evidence	Operational decision
Premium fluid milk	Composition, SCC, microbial load, residues, sensory consistency	Certification + FTIR/MIR + risk-based isotope/fatty-acid checks	Accept, hold, or confirm batch
Yoghurt/kefir	Protein functionality, lactose, starter activity, inhibitor absence	Supplier traceability + matrix-specific spectra	Release fermentation lot
Cheese	Casein/fat ratio, minerals, SCC, coagulation, spores	Fatty acids + spectra + farm records	Standardize and allocate milk
Butter/ghee/cream	Fat purity, oxidation, free fatty acids	ATR-FTIR/GC with targeted confirmation	Prevent vegetable-oil substitution
Milk powder/infant ingredients	AFM1, residues, oxidation, microbiology, reconstitution	LC/GC-MS, isotope framework, digital chain of custody	High-stringency release
Functional dairy	Verified omega-3, CLA, peptides, micronutrients; shelf-life stability	Targeted chemistry + label compliance	Authorize substantiated claims
Traceability services	Certificate integrity, audit trail, model version, uncertainty	Linked documentary and analytical evidence	Investigate anomalies and support recalls

10. CRITICAL SYNTHESIS

10.1 What can be stated with reasonable confidence?

Organic milk is milk produced under a certified management system. In forage-based systems the composition is not set and frequently allows the lipid percentage to change in favor of higher n-3 fatty acids and CLA. The chemical composition,

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minerals, microbiological indicators, pollutants and sensory qualities are quite diverse. Certification is not the same as safety. Organic milk requires as much behavior discipline in the same areas as any premium dairy stream. That is: mastitis, cleanliness, chilling, spores, antibiotic residues, pesticides, heavy metals, aflatoxin M1 etc. Zero-risk terminology is not scientific, but the probable risk profile may be different (Fusco *et al.,* 2020; Costa *et al.,* 2024; Boudebbouz *et al.,* 2022; Boudebbouz *et al.,* 2021; Jahromi *et al.,* 2025).

10.2 Why Published Classification Accuracies Are Often Too Optimistic?

Geographically restricted, seasonally limited sample collections for authenticity investigations often show obvious group separation with controlled instrumentation. Random splits of the train-test sets might result in both samples being distinct yet similar. Models are thus likely to break down for new farms, years, instrumentation, processing histories and heterogeneous feeding systems. Therefore, external validation is more informative than merely internal cross-validation (Grassi *et al.,* 2023; Xu *et al.,* 2025; Julmohammad *et al.,* 2025; Chung *et al.,* 2022).

Analytical models also face decisions on pre-processing the spectrum, feature selection, class imbalance and out-of-domain data. A pragmatic procedure would record such judgments, keep raw data, lock the model against retesting and communicate uncertainty. Interpretation is important if it has an influence on certification, payment or regulatory action (Ribeiro *et al.,* 2023; Zhao *et al.,* 2023; Liang *et al.,* 2025).

10.3 Limitations of the evidence base

The literature is mostly west-oriented and varies in technique in terms of research. Organic standards are different in each jurisdiction, many studies have small sample sets, seasonal coverage is sometimes incomplete, and analytical units or sample matrices are not always comparable. Publication bias might be towards positive differences or extremely accurate classifiers. The applicability of the analytical concepts is also shown by analyses of other species and dairy matrices; however, they cannot be applied to organic cow milk at the same time. The benefits of volunteering are extensively proven (Arifah *et al.,* 2022; Chu *et al.,* 2023; Yao *et al.,* 2023; Duliński *et al.,* 2025).

Another drawback is the health evidence. The heterogeneity in fatty acids or micronutrients does not suggest the clinical result will be different. There are few randomized trials of organic vs conventional milk. Interpretations should not transform compositional differences into disease prevention claims (Badawy *et al.,* 2023; Lumsden *et al.,* 2023; Wallace *et al.,* 2021).

11. GAPS IN THE RESEARCH AND FUTURE DIRECTIONS

Multicounty reference databases are necessary first. Certifiable farms and non-certifiable comparators matched, several breeds, seasons, lactation phases, climate zones, processing conditions all covered. Feed mix, availability to pasture and vet treatment storage and instrument settings. With such data sets we could do true external validation and evaluate how much variation is attributable to certification vs the underlying management system. It is already in the form of a reference, which you specified in the preceding sentence is allowed to include.

Second, analytical procedures should be harmonized. Research studies should involve sample design, chain of custody, successful reference techniques, calibration traceability, detection/quantification limitations, uncertainty, preprocessing, feature selection model version, and application domain. Open spectrum libraries and inter-laboratory transfer studies would increase the reproducibility of the results (Ashraf *et al.,* 2024; Ceniti *et al.,* 2023; Mendes and Duarte, 2021).

The future of authentication should be the integration, not concatenation, of evidence. Bayesian or ensemble frameworks might incorporate certificate risk, fatty acids, isotopes, spectra, residues and geography with retaining uncertainty and interpretability. Anomaly detection is especially interesting since it might possibly detect novel kinds of fraud, without pushing every sample into the recognized groups (O'Sullivan *et al.,* 2023; Hou *et al.,* 2023; Chung *et al.,* 2022; Varzakas, 2023).

Fourth, industrial studies need to examine options. The relevant outcomes include the economic value of the false release, needless hold, testing expense, delay to decision, model drift and confirmatory tests. Portable equipment must be compared with certified laboratory procedures in actual receiving-dock situations, and not just within laboratory controlled tests (de Freitas *et al.,* 2025; Gullifa *et al.,* 2025; Liang *et al.,* 2025).

12. CONCLUSION

Organic milk derives from a certification procedure that affects the chemical and qualitative features. These include interplay of feed, grazing, breed, season, animal and farm cleanliness and processing and storage. There is no data from 2020 to 2025 to support the blanket assumption that all organic milk samples have a better gross composition, safety or health impacts. In almost every organic system we have looked at, harvesting the forages causes the change in composition that you would predict from having more n-3 fatty acids and CLA being produced. Context dependency is still present in mineral and micronutrient and microbial ecology and somatic cell count, sensory qualities and contaminant occurrence of a product.

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The authentication hence must be seen as a multivariate proof issue. Legally, it relies on chain-of-custody records and certification. Analytically, it relies on fatty-acid profiling, stable-isotope ratios, FTIR/MIR/NIR spectroscopy, chromatography, NMR, and residues screening and categorization. Machine learning may also improve the efficiency of screening using fast spectroscopy. But good internal correctness does not imply industrial validity. There must be external blind validation, seasonal and geographic robustness, instrument-transfer evaluation, reporting of uncertainty and confirmatory reference procedures.

The most viable approach for industry is an integrated workflow that links certified suppliers, representative sampling, quality and safety testing, authenticity screening, and risk-based confirmation. This may assist in the preservation of premium fluid milk, fermented products, cheese, butter, ghee, milk powders, functional foods and export-oriented traceability systems. We think that the future of quality assurance in organic milk is not in a single biomarker but in an open, auditable mix of documentary and analytical data.

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