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Technological Innovations in Antibiotic Residue Detection in Milk: Integrating Biosensors and Machine Learning for Dairy Surveillance in India

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ABSTRACT

The widespread use of antibiotics in dairy farming has raised growing concerns regarding the presence of antibiotic residues in milk, particularly in countries with highly decentralized and smallholder-dominated production systems such as India. Residual antibiotics pose significant public health risks including allergic reactions and antimicrobial resistance. Conventional laboratory-based detection techniques, such as chromatographic and microbiological assays, provide high analytical reliability but remain constrained by high costs, specialized infrastructure requirements, and limited suitability for rapid on-site screening in rural dairy networks. This study critically reviews recent technological innovations for antibiotic residue detection in milk, with particular emphasis on electrochemical biosensors, metal–organic framework–based sensing platforms, and machine learning–assisted analytical systems. The analysis evaluates their analytical performance, detection sensitivity, operational feasibility, and applicability within decentralized milk collection systems. Results indicate that biosensor technologies provide promising capabilities for rapid field-level screening, while machine learning approaches enhance signal interpretation and enable data-driven monitoring. Building on these findings, the study proposes a technology adoption framework tailored to the structural characteristics of the Indian dairy sector. The framework integrates frontline biosensor screening at milk collection centers with centralized laboratory confirmation and machine learning–enabled digital surveillance. Regulatory, economic, and operational barriers affecting technology adoption are also identified, along with potential mitigation strategies. By linking technological innovation with institutional and operational considerations, the study contributes a context-sensitive framework for strengthening antibiotic residue monitoring in India's dairy value chain.

Keywords: Antibiotic residues; milk safety; biosensors; machine learning; dairy sector; residue monitoring.

1. Introduction

1.1 Antibiotic Residues in Milk and Emerging Food Safety Concerns

Milk and dairy products are essential components of human nutrition and agricultural economies worldwide. In India, the dairy sector plays a particularly significant role in rural livelihoods and food security, with milk production largely supported by smallholder farmers operating within cooperative and informal collection systems. While this decentralized production structure supports economic inclusion, it also creates challenges for quality assurance and food safety monitoring across widely dispersed supply chains (Banerjee et al., 2024; Sharma et al., 2022). One major concern in dairy production is the presence of antibiotic residues in milk. Antibiotics are frequently used in dairy animals for treatment of infections such as mastitis and other veterinary purposes. When recommended withdrawal periods are not followed or veterinary oversight is limited, residues may persist in milk entering the food supply chain (Kurjogi et al., 2019). Several studies across India have reported the presence of antibiotic classes such as β- lactams, tetracyclines, and sulfonamides in milk samples (Moudgil et al., 2019; Kumar et al., 2022; Vijay et al., 2022). These residues pose significant public health risks, including allergic reactions, disruption of intestinal microbiota, and antimicrobial resistance (AMR) (Sahoo et al., 2023). In addition, antibiotic residues may interfere with dairy fermentation processes and compromise compliance with international food safety standards such as those established by the Codex Alimentarius Commission (Navrátilová et al., 2024). These concerns highlight the need for effective monitoring systems capable of detecting residues across complex dairy supply chains.

1.2 Limitations of Conventional Detection Approaches

Several analytical techniques are used to detect antibiotic residues in milk, including microbial inhibition assays, immunoassays, and chromatographic methods coupled with mass spectrometry. These approaches differ in

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sensitivity, specificity, and operational complexity and are widely applied in food safety laboratories and regulatory monitoring programs (Vercelli et al., 2023; Navrátilová et al., 2024).

Chromatographic techniques such as liquid chromatography–tandem mass spectrometry (LC– MS/MS) are considered the reference method due to their high sensitivity and ability to detect multiple antibiotic residues simultaneously (Vercelli et al., 2023). However, these methods require advanced laboratory infrastructure, specialized technical expertise, and high operational costs, limiting their routine application to centralized laboratories.

Rapid screening methods, including microbial inhibition assays and immunoassays, provide faster and lower-cost alternatives but may suffer from cross-reactivity, matrix interference, and variable sensitivity across antibiotic classes (Cardozo et al., 2018; Schneider et al., 2019). Analytical outcomes may also be influenced by environmental conditions and sample handling.

These limitations highlight the need for complementary detection technologies that enable rapid and reliable residue screening closer to the point of milk collection.

1.3 Emerging Biosensor Technologies for Antibiotic Detection

Recent advances in biosensor technology have created new opportunities for detecting antibiotic residues in food matrices. These systems integrate biological recognition elements, such as antibodies, enzymes, or aptamers, with physicochemical transducers that convert biochemical interactions into measurable signals (Liu et al., 2022; Pohanka, 2025).

Among the various platforms, electrochemical biosensors have attracted particular attention because of their high sensitivity, rapid response time, and compatibility with portable analytical devices (Majdinasab et al., 2017). Such systems can detect trace levels of antibiotics in complex matrices such as milk while requiring minimal sample preparation (Aliev et al., 2022; Chawla et al., 2021).

Advances in sensing materials have further improved analytical performance. Metal–organic frameworks (MOFs), characterized by high surface area and tunable chemical structures, have been incorporated into sensor platforms to enhance analyte adsorption and signal amplification. MOF-based sensors demonstrate promising sensitivity and selectivity for detecting multiple antibiotic classes in dairy matrices (Rayappa et al., 2023), offering potential for decentralized screening at early stages of the dairy supply chain.

More recently, integration of biosensor platforms with artificial intelligence–based analytical tools has been explored to improve signal interpretation and enable real-time monitoring of antibiotic residues in food systems (Nallasamy et al., 2025; Zhou et al., 2024).

1.4 Machine Learning Applications in Residue Detection

Advances in data-driven analytical methods have also contributed to improvements in residue detection technologies. Machine learning techniques have increasingly been integrated with biosensor platforms to improve detection accuracy and enable automated interpretation of analytical signals in food safety monitoring systems (Aliev et al., 2022; Nallasamy et al., 2025).

Algorithms such as artificial neural networks, support vector machines, and random forest models have been applied to classify antibiotic residues and predict their concentrations. These approaches help improve detection accuracy by reducing noise and matrix interference in analytical data (Zhou et al., 2024).

Integration of machine learning with sensor technologies enables automated interpretation of analytical signals and supports the development of intelligent detection systems capable of rapid decision-making. Such systems may facilitate real-time monitoring and digital data integration within food safety surveillance frameworks.

1.5 Feasibility Challenges in the Indian Dairy Context

Despite the analytical potential of advanced detection technologies, their adoption in the Indian dairy sector depends on several contextual factors. Dairy production in India is highly decentralized, with milk collected from millions of smallholder farmers through cooperative and informal networks. Quality assessment at milk collection centers often requires rapid decisions regarding milk acceptance.

Infrastructure limitations pose additional challenges. Rural collection centers frequently operate with limited

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laboratory facilities, variable electricity supply, and restricted access to trained technical personnel. Environmental conditions such as high temperature and humidity may also influence analytical performance (Banerjee et al., 2024). Economic considerations are equally important. Detection technologies must be affordable and easy to operate for cooperatives and local collection centers. Systems requiring complex instrumentation or specialized training may face barriers to widespread adoption despite their analytical advantages.

1.6 Research Contribution and Conceptual Positioning

Although significant research has examined analytical techniques for detecting antibiotic residues in milk, much of the literature focuses either on laboratory-based detection methods or on individual sensor technologies. Few studies integrate technological innovations with practical implementation strategies for decentralized dairy systems. This study addresses this gap by synthesizing recent advances in biosensor technologies and machine learning–supported analytical methods for antibiotic residue detection in milk. The analysis evaluates their analytical performance and operational feasibility within the Indian dairy context.

Based on this synthesis, the study proposes a technology adoption framework for integrating advanced detection technologies into dairy monitoring systems, linking field-level screening technologies with centralized confirmatory testing and digital surveillance mechanisms. By connecting technological innovation with practical deployment considerations, the research contributes to strengthening antibiotic residue monitoring in India's dairy value chain. Accordingly, this study critically reviews emerging biosensor and machine learning–based detection technologies for antibiotic residues in milk and to develop a conceptual framework for their feasible integration into residue surveillance systems within the Indian dairy sector.

2. Methodology

2.1 Literature Identification and Selection

This study adopts a structured qualitative research design based on systematic literature synthesis and comparative technological evaluation. Rather than generating primary experimental data, the research consolidates and analyzes existing scientific evidence on technologies for detecting antibiotic residues in milk. This approach is appropriate for evaluating emerging detection technologies and assessing their potential application within complex dairy supply chains.

Relevant literature was identified through searches of major scientific databases including Scopus, PubMed, Web of Science, ScienceDirect, and Google Scholar. Search queries combined keywords related to antibiotic residues and emerging analytical technologies. Search terms included antibiotic residues in milk, biosensors, electrochemical sensors, machine learning food safety, and dairy residue monitoring. These keywords were used individually and in combination to capture both technological and food safety perspectives.

The literature search focused primarily on peer-reviewed publications between 2000 and 2025 to include both established analytical methods and recent technological innovations. Additional sources included regulatory and policy documents from international food safety organizations and national authorities addressing veterinary drug residues in food systems (Codex Alimentarius Commission, 2022; Navrátilová et al., 2024).

Inclusion criteria required that studies (i) address antibiotic residue detection in milk or dairy matrices, (ii) provide methodological or performance-related data for analytical techniques, or (iii) discuss technological applications relevant to food safety monitoring. Studies focused exclusively on non-dairy matrices such as meat or aquaculture products were excluded unless the methodological findings were transferable to milk analysis. Publications lacking sufficient methodological transparency or empirical validation were also excluded. This selection process ensured that the analysis was based on scientifically credible and relevant evidence.

2.2 Analytical Framework for Technology Evaluation

To enable systematic comparison across different detection technologies, an analytical evaluation framework was developed based on criteria commonly applied in analytical chemistry and food safety monitoring research (Reig et al., 2020; Vercelli et al., 2023). The framework was designed to assess both the analytical performance and practical applicability of residue detection methods.

The first dimension of the evaluation focused on analytical performance indicators, including sensitivity, specificity,

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detection limits, and reproducibility. Sensitivity refers to the ability of a method to detect antibiotic residues at concentrations below established maximum residue limits (MRLs), while specificity reflects the capacity to accurately distinguish target compounds from
structurally similar substances or matrix interferences. Detection limit and quantification capability were examined using performance metrics reported in validation studies.

The second dimension assessed operational and economic considerations, including cost of analysis, instrumentation requirements, and technical expertise needed for routine implementation. These factors are particularly important when evaluating technologies for deployment in decentralized dairy systems where laboratory infrastructure may be limited.

The third dimension focused on practical usability and field applicability. Parameters such as analysis time, portability of detection devices, sample preparation requirements, and robustness under variable environmental conditions were considered. These factors influence whether a technology can be applied at farm level, milk collection centers, cooperative laboratories, or only within specialized analytical facilities.

Using this framework, conventional laboratory-based analytical techniques and emerging detection technologies were comparatively evaluated to determine their potential roles within residue monitoring systems.

2.3 Technology Feasibility and Framework Development

Building on the analytical evaluation, the study assessed the feasibility of emerging detection technologies within the operational context of the Indian dairy sector. Particular attention was given to biosensor-based detection systems and machine learning–supported analytical models because of their potential for decentralized residue monitoring. Electrochemical biosensors and metal–organic framework–based sensing platforms were examined due to their increasing prominence in recent analytical research (Rayappa et al., 2023; Aliev et al., 2022). The analysis considered factors such as detection sensitivity, sensor stability, portability, and compatibility with milk matrices to evaluate their suitability for use outside controlled laboratory environments.

The potential integration of machine learning algorithms with sensor-based detection systems was also assessed. Techniques such as artificial neural networks and support vector machines have been shown to enhance signal interpretation and improve classification accuracy for antibiotic detection in complex food matrices (Nallasamy et al., 2025). These approaches can enable automated interpretation of sensor signals and support rapid decision-making in field settings.

Feasibility analysis also incorporated contextual factors affecting technology deployment in Indian dairy systems, including infrastructure availability, operator skills, environmental conditions, and economic constraints within milk collection networks (Banerjee et al., 2024).

The findings were subsequently synthesized to develop a conceptual technology adoption framework for antibiotic residue detection in the Indian dairy sector. The framework links decentralized screening technologies, such as portable biosensors, with centralized confirmatory testing and digital data integration to support coordinated residue surveillance across the dairy value chain.

3. Results and Discussion

3.1 Comparative Performance of Conventional and Advanced Antibiotic Residue Detection Technologies

Comparative analysis of conventional laboratory-based analytical methods and emerging biosensor technologies reveals distinct differences in analytical capability and operational applicability within the Indian dairy context. Chromatographic techniques such as high- performance liquid chromatography (HPLC) and liquid chromatography–tandem mass spectrometry (LC–MS/MS) demonstrate high sensitivity, specificity, and reproducibility for detecting a wide range of antibiotic residues in milk. These methods enable precise quantification of residues at trace concentrations and remain the reference standards for confirmatory testing and regulatory enforcement in food safety surveillance systems (Vercelli et al., 2023; Navrátilová et al., 2024).

Despite their analytical robustness, chromatographic methods face significant operational constraints. These techniques require specialized laboratory infrastructure, skilled personnel, extensive sample preparation, and relatively long analysis times, which limit their applicability for routine monitoring in decentralized dairy systems. In

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Vol. 01, Issue 5, September 2026, pp :143-155

rural milk collection networks dominated by smallholder producers, the reliance on centralized laboratory testing can delay contamination detection and reduce the effectiveness of preventive quality control measures (Banerjee et al., 2024).

Emerging biosensor-based detection technologies offer an alternative approach focused on rapid and decentralized screening. Electrochemical and nanomaterial-enhanced biosensors demonstrate the capability to detect antibiotic residues at concentrations approaching regulatory thresholds while enabling rapid analysis and minimal sample preparation (Aliev et al., 2022; Rayappa et al., 2023). Although these systems may exhibit slightly lower analytical precision compared with laboratory-based methods, their operational advantages make them particularly suitable for preliminary screening applications. Consequently, biosensor technologies are increasingly considered complementary tools within tiered residue monitoring systems that combine rapid field-level detection with confirmatory laboratory analysis (Banerjee et al., 2024).

3.2 Analytical and Operational Performance of Electrochemical Biosensors

Electrochemical biosensors represent one of the most widely investigated categories of advanced detection technologies for antibiotic residues in milk (Majdinasab et al., 2017; Singh et al., 2023). These sensors typically employ biological recognition elements such as antibodies, aptamers, or molecularly imprinted polymers to selectively bind target antibiotic molecules (Zhou et al., 2015). The resulting biochemical interactions generate measurable electrical signals that correlate with analyte concentration, enabling rapid and sensitive detection (Fang et al., 2021; Liu et al., 2021).

Recent studies demonstrate that electrochemical biosensors can achieve detection limits in the nanogram per liter range with analysis times of only a few minutes, representing a substantial improvement in operational speed compared with conventional chromatographic techniques (Aliev et al., 2022). Minimal sample preparation requirements further enhance their applicability in field settings where laboratory infrastructure and technical expertise may be limited. These characteristics make electrochemical biosensors particularly suitable for screening applications at milk collection centers and cooperative testing facilities.

From an operational perspective, electrochemical biosensors also offer advantages such as portability, low power consumption, and compatibility with compact electronic interfaces. Advances in nanomaterial-enhanced electrodes and signal amplification strategies have further improved sensor sensitivity and stability, expanding their potential for real-time food safety monitoring (Zhu et al., 2021; Zhang et al., 2024; Bibani et al., 2025). Several prototypes have been successfully integrated into handheld or portable devices capable of operating under variable environmental conditions (Singh et al., 2023; Zhang et al., 2024). However, challenges remain regarding long-term sensor stability, reproducibility across different milk matrices, and large-scale field validation. Fouling of sensor surfaces by proteins and lipids present in milk may affect analytical performance during repeated use, requiring appropriate surface modification or maintenance protocols. Additionally, most reported biosensor systems have been evaluated under controlled laboratory conditions, and further studies are needed to assess their reliability in real-world dairy monitoring environments (Nath, 2024).

3.3 Enhancement of Detection Sensitivity Through Metal Organic Framework Based Sensors

Metal-organic framework (MOF)-based sensors represent an important advancement in materials used for antibiotic residue detection (Oladipo et al., 2023). These porous crystalline materials possess exceptionally high surface area, tunable pore structures, and customizable functional groups, which enhance analyte adsorption and signal amplification in sensing platforms (Rayappa et al., 2023). Incorporation of MOF materials into electrochemical or voltametric sensors has therefore been shown to significantly improve detection sensitivity and reduce detection limits for several classes of veterinary antibiotics (Abdullatif et al., 2025).

Studies demonstrate that MOF-modified electrodes exhibit strong affinity toward multiple antibiotic molecules, enabling detection of diverse residue classes within complex matrices such as milk (Liang et al., 2023). This multi-analyte detection capability is particularly valuable in dairy surveillance systems where antibiotic usage patterns are heterogeneous and residues from different therapeutic classes may occur simultaneously (Jia et al., 2020). By increasing analyte capture efficiency and improving signal transduction, MOF-based sensors can achieve analytical

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editor@ijemss.com
Vol. 01, Issue 5, September 2026, pp :143-155

performance approaching that of more complex laboratory techniques while maintaining the operational advantages of biosensor platforms.

The tunable structure of MOFs also allows optimization of pore size and surface chemistry to selectively target specific antibiotic molecules. Such modifications improve selectivity and reduce non-specific interactions in complex biological matrices, thereby enhancing detection reliability (Rayappa et al., 2023). As a result, MOF-based biosensors are increasingly explored as high-sensitivity screening tools capable of bridging the performance gap between portable biosensors and laboratory-based analytical methods.

A broader comparison of recent biosensor platforms used for antibiotic residue detection in milk is summarized in Table 1. The table highlights the diversity of emerging sensing strategies, including electrochemical immunosensors, aptamer-based sensors, nanomaterial-enhanced electrodes, MOF-based platforms, and machine learning–assisted biosensing systems. These technologies demonstrate detection limits ranging from nanogram-per-liter levels to sub-nanomolar concentrations while offering advantages such as rapid analysis, portability, and compatibility with field deployment (Aliev et al., 2022; Tao et al., 2020; Zhou et al., 2024). Notably, MOF-based sensors and nanomaterial-enhanced electrochemical biosensors show strong potential for achieving high sensitivity while maintaining relatively simple analytical workflows.

Despite these advantages, several challenges remain regarding the large-scale implementation of MOF-based sensing platforms. Fabrication of MOF materials often involves complex synthesis procedures that can increase production costs and limit scalability. In addition, stability under variable temperature and humidity conditions remains an important consideration for deployment in rural dairy environments (Rayappa et al., 2023). Most reported applications also remain at the laboratory validation stage, with limited long-term field testing in real dairy supply chains.

Consequently, while MOF-based biosensors demonstrate strong analytical promise, further research focusing on sensor durability, cost-effective fabrication, and field validation will be essential before widespread adoption in decentralized milk monitoring systems can be achieved.

As summarized in Table 1, aptamer-based sensors and nanomaterial-enhanced electrochemical biosensors demonstrate extremely low detection limits and rapid analysis times, highlighting their potential for rapid food safety monitoring.

Table 1. Comparison of Recent Biosensor Technologies for Antibiotic Residue Detection in Milk.

Detection limits vary depending on sensor configuration, matrix conditions, and signal amplification strategies.

Biosensor Type	Recognition Element	Target Antibiotics	Detection Limit	Key Advantages	Limitations	References
Electrochemical immunosensor	Antibody	Penicillin, streptomycin	ng/L–µg/L	High selectivity and quantitative detection	Antibody stability issues	Singh et al., 2023
Electrochemical aptasensor	DNA aptamer	Kanamycin	$\sim 10^{-4}$ µM	High sensitivity and rapid detection	Requires aptamer optimization	Zhou et al., 2015
MOF-based electrochemical biosensor	MOF-modified electrode + aptamer	Tobramycin	ng/L	Signal amplification and multi-analyte potential	Complex synthesis processes	Oladipo et al., 2023
Nanomaterial-enhanced	AuNPs / carbon	Tetracycline	$\sim 10^{-4}$ µM	High sensitivity	Nanomaterial cost and	Zhang et al., 2024

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electrochemical biosensor	nanofibers			and improved electron transfer	stability	
Colorimetric aptasensor	DNA aptamer + enzyme amplification	Kanamycin	10^{-12} µM	Ultra-low detection limit and visual detection	Limited multiplex capability	Liu et al., 2021
Fluorescent aptasensor	Aptamer + fluorescent dye	Enrofloxacin	~10^{-4} µM	High sensitivity and simple optical detection	Requires fluorescence instrumentation	Tao et al., 2020
Smartphone-based aptamer biosensor	Mutated aptamer + colorimetric detection	Multiple antibiotics	~0.15 nmol/mL	Portable and instrument-free detection	Calibration variability	Zhang et al., 2024
Electrochemical aptasensor with nanostructured gold electrode	Aptamer immobilized on Au nanostructures	Vancomycin	~1.7 nM	Disposable, portable sensor	Limited field validation	Bibani et al., 2025
MOF-based voltammetric sensor	Cu/Ni-MOF electrode	Sulfadimidine	~100 µg/L	High adsorption capacity and sensitivity	Fabrication complexity	Abdullatif et al., 2025
ML-assisted electrochemical biosensor	Sensor + machine learning model	Multiple antibiotic classes	Variable (ng/L range)	Improved signal interpretation and automated detection	Requires training datasets	Aliev et al., 2022; Zhou et al., 2024; Nallasamy et al., 2025

3.4 Role of Machine Learning in Improving Detection Accuracy and Decision Making

Machine learning (ML)-assisted analytical models are increasingly used to enhance the accuracy and reliability of antibiotic residue detection systems (Hassan et al., 2025). By analyzing complex datasets generated by biosensors or spectroscopic instruments, ML algorithms can identify patterns and correlations that may not be easily detected through conventional signal analysis. This capability is particularly valuable in milk matrices, where variability in composition, temperature, and handling conditions can influence analytical signals (Aliev et al., 2022; Ren et al., 2024; Zhou et al., 2024).

Supervised learning approaches such as artificial neural networks and support vector machines are commonly applied to classify antibiotic residues and estimate concentration levels. These models improve detection reliability by reducing false positives and false negatives caused by noise or matrix interference. In several studies, ML

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Vol. 01, Issue 5, September 2026, pp :143-155

integration has enabled quantitative prediction of residue concentrations, thereby supporting compliance assessment with maximum residue limits rather than simple presence–absence screening (Aliev et al., 2022; Nallasamy et al., 2025).

In addition to improving analytical accuracy, ML algorithms facilitate automation and scalability in residue monitoring systems. Embedded computational models allow sensor platforms to generate clear analytical outputs without requiring manual interpretation of raw signals. Such automated decision support is particularly beneficial in decentralized dairy systems where operator expertise may be limited. ML-enabled systems also support aggregation of detection data across multiple locations, enabling trend analysis and evidence-based surveillance of antibiotic use and contamination patterns (Zhou et al., 2024; Nallasamy et al., 2025).

Despite these advantages, the performance of ML-assisted detection systems depends heavily on the availability of representative training datasets. Inadequate or biased datasets may limit model generalizability across different geographic regions or production environments. Additionally, computational requirements and digital infrastructure constraints may affect implementation in rural settings (Shukla et al., 2018). Consequently, machine learning should be considered an enabling component that enhances sensor-based detection systems rather than a standalone analytical solution.

3.5 Feasibility of Advanced Detection Technologies in Rural Dairy Collection Systems

The feasibility assessment indicates that biosensor-based detection technologies are generally more compatible with rural milk collection systems than conventional laboratory-based analytical methods. Portable sensor platforms, rapid analysis times, and minimal infrastructure requirements align well with the operational conditions of cooperative milk collection centers. Field-level screening also enables immediate identification of contaminated milk before aggregation, reducing reliance on centralized laboratories and enabling timely corrective actions (Banerjee et al., 2024; Rayappa et al., 2023).

However, successful deployment depends on several contextual factors beyond analytical performance. Infrastructure availability, including reliable electricity supply and equipment maintenance capacity, can significantly influence operational sustainability. Technologies that require complex calibration procedures, specialized consumables, or advanced technical expertise may face practical limitations in rural settings (Shukla et al., 2018). Institutional support structures also play an important role in facilitating technology adoption. Integration of detection technologies within cooperative management systems, operator training programs, and established quality assurance protocols increases the likelihood of sustained implementation. Studies of technology adoption in agri-food systems emphasize that detection tools must be embedded within existing operational workflows to ensure long-term effectiveness (Kaushik & Rajwanshi, 2025).

Stakeholder acceptance further influences implementation outcomes. Detection systems that provide clear operational benefits, such as protecting cooperative milk quality and reducing economic losses from contaminated batches are more likely to gain support from farmers and collection centers. In contrast, stand-alone technologies introduced without institutional integration often experience limited long-term adoption.

3.6 Integrated Interpretation and Implications for the Indian Dairy Sector

The preceding analysis indicates that no single detection technology can adequately address antibiotic residue monitoring across India's diverse dairy production systems. Instead, the findings support a tiered detection strategy in which complementary technologies perform distinct roles within the surveillance framework. Conventional chromatographic methods such as LC–MS/MS remain essential for confirmatory testing due to their high analytical sensitivity and regulatory acceptance (Vercelli et al., 2023; Navrátilová et al., 2024). However, their infrastructure requirements limit routine use in decentralized milk collection systems. Emerging biosensor technologies offer a practical alternative for rapid field-level screening. Electrochemical biosensors and nanomaterial-enhanced sensors provide adequate sensitivity for preliminary residue detection while enabling portable and rapid analysis (Aliev et al., 2022; Rayappa et al., 2023). Machine learning–assisted models further enhance these systems by improving signal interpretation and enabling automated monitoring (Zhou et al., 2024; Nallasamy et al., 2025).

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Vol. 01, Issue 5, September 2026, pp :143-155

Overall, effective residue surveillance requires integration of decentralized screening, laboratory confirmation, and digital monitoring systems adapted to the operational realities of the Indian dairy sector (Banerjee et al., 2024; Sajja & Dave, 2019).

3.7 Technology Adoption Framework for Antibiotic Residue Detection in the Indian Dairy Sector

The findings support the development of a structured technology adoption framework for antibiotic residue monitoring in the Indian dairy sector. Given the diversity of production systems and infrastructural variability across the dairy value chain, an integrated and tiered surveillance approach combining decentralized screening with centralized

confirmatory analysis provides the most feasible monitoring strategy. As illustrated in Figure 1, the proposed framework links field-level biosensor screening with laboratory confirmation and digital surveillance systems to support coordinated residue monitoring (Banerjee et al., 2024; Navrátilová et al., 2024).

3.7.1 Deployment of Biosensor Technologies at Milk Collection Centers

Within the proposed framework, biosensor technologies function as frontline screening tools at milk collection centers, particularly within cooperative dairy networks. In India's decentralized dairy system, milk from numerous smallholder farmers is pooled at village-level collection points before transportation to processing facilities (Banerjee et al., 2024; Dixit et al., 2024). Early-stage screening at these locations is therefore critical to prevent contaminated milk from entering aggregated supplies.

Portable biosensor platforms, especially electrochemical sensors and handheld detection devices, are well suited for field-level deployment due to their rapid response time, portability, and minimal sample preparation requirements (Aliev et al., 2022; Rayappa et al., 2023). Screening prior to milk aggregation allows cooperative operators to rapidly identify and reject contaminated milk, thereby reducing the risk of residue contamination across pooled batches. This frontline screening role complements laboratory testing by identifying samples that require confirmatory analysis.

3.7.2 Integration with Regulatory Monitoring Systems

Effective residue surveillance also requires integration of screening technologies with national regulatory monitoring systems. In India, oversight of veterinary drug residues in dairy products is guided by the Food Safety and Standards Authority of India (FSSAI) and national surveillance programs such as the Residue Monitoring Plan (RMP). Within this regulatory framework, a tiered detection model can improve monitoring efficiency. Tier 1 screening is conducted using rapid biosensor technologies at collection centers, while Tier 2 confirmation is performed in centralized laboratories using chromatographic methods such as LC–MS/MS, which remains the reference standard for multi-residue detection (Vercelli et al., 2023; Navrátilová et al., 2024). This approach enables high-frequency screening at decentralized points while maintaining analytical accuracy for regulatory enforcement.

3.7.3 Digital Dairy Surveillance and Data Integration

The adoption framework further incorporates digital surveillance and data integration mechanisms to support coordinated residue monitoring. Machine learning algorithms can enhance biosensor performance by improving signal interpretation and enabling automated classification of analytical outputs (Zhou et al., 2024; Nallasamy et al., 2025).

Integration of biosensor platforms with digital reporting systems enables real-time transmission of screening results from milk collection centers to cooperative management systems and regulatory databases (Charlebois & Haratifar, 2024; Zhang et al., 2024). Such digital integration supports centralized monitoring, trend analysis, and early detection of contamination events. By combining decentralized screening technologies with machine learning–enabled data analysis and centralized reporting, the framework strengthens national residue surveillance capacity and supports evidence-based regulatory decision-making.

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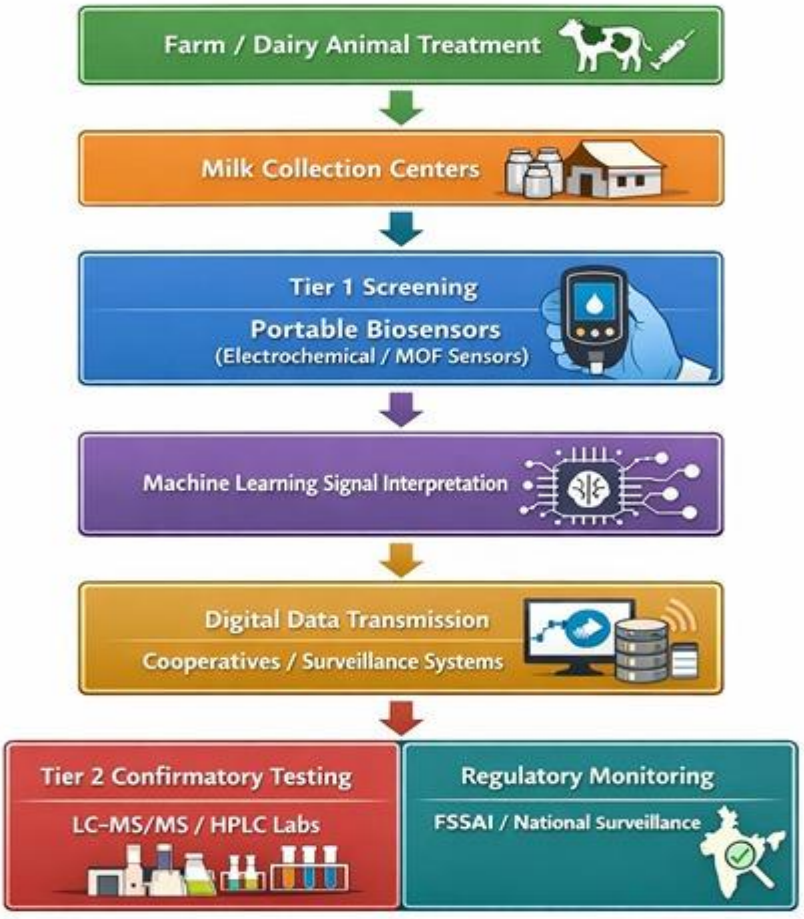
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Vol. 01, Issue 5, September 2026, pp :143-155

Figure 1. Technology Adoption Framework for Antibiotic Residue Detection in the Indian Dairy Sector



3.8 Regulatory, Economic, and Operational Barriers and Mitigation Strategies

Despite the technological advances described in preceding sections, several regulatory, economic, and operational barriers continue to influence the adoption of advanced antibiotic residue detection technologies in the Indian dairy sector.

Regulatory barriers remain a major challenge for emerging biosensor-based detection platforms. Although these technologies demonstrate strong potential for rapid screening, many lack standardized validation protocols and formal recognition within existing food safety frameworks. In India, residue monitoring is largely based on centralized laboratory testing aligned with national standards and international guidelines such as those of the Codex Alimentarius Commission (Codex Alimentarius Commission, 2022; FSSAI, 2023). Consequently, biosensor systems are often limited to preliminary screening roles rather than being integrated into official monitoring programs. A phased validation strategy, where biosensor screening operates
alongside reference laboratory methods such as LC–MS/MS, may provide a practical pathway for regulatory integration (Tittlemier & Lau, 2019; Vercelli et al., 2023).

Economic constraints also influence technology adoption in India's smallholder-dominated dairy systems. High initial costs, consumables, and maintenance requirements may discourage adoption at cooperative collection centers. Cooperative-level cost sharing, targeted subsidies, and integration of residue testing within broader dairy quality improvement programs can improve economic feasibility (Banerjee et al., 2024; Dixit et al., 2024).

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Vol. 01, Issue 5, September 2026, pp :143-155

Operational challenges further affect sustainability, particularly where technical expertise and infrastructure are limited. Technologies requiring complex calibration or continuous connectivity may be difficult to implement in rural settings. Aligning technology design with user capabilities and strengthening institutional support systems can significantly improve adoption outcomes (Kaushik & Rajwanshi, 2025).

4. Conclusion

Antibiotic residues in milk remain an important challenge for food safety governance, public health protection, and dairy supply chain management, particularly in India's highly decentralized dairy sector dominated by smallholder production and cooperative milk collection systems. Conventional laboratory-based monitoring methods, while analytically reliable, are limited in their ability to support rapid and widespread residue surveillance in such distributed production environments.

This study reviewed recent technological advances in antibiotic residue detection, focusing on electrochemical biosensors, metal–organic framework–based sensing materials, and machine learning–assisted analytical systems. The findings indicate that although chromatographic techniques remain essential for confirmatory testing and regulatory enforcement, emerging biosensor technologies provide practical solutions for rapid, portable, and cost-effective screening at early stages of the dairy supply chain. Integration of machine learning algorithms further enhances detection accuracy and enables automated interpretation of analytical signals.

A key contribution of this study is the development of a technology adoption framework tailored to the structural characteristics of the Indian dairy sector. The proposed framework integrates biosensor-based screening at milk collection centers with centralized laboratory confirmation and digital data integration, enabling coordinated and high-frequency residue monitoring.

The analysis also highlights that successful implementation of advanced detection technologies depends not only on analytical performance but also on supportive regulatory frameworks, economic feasibility, and institutional capacity. Strengthening residue surveillance therefore requires coordinated efforts involving regulatory agencies, dairy cooperatives, technology developers, and producers.

Overall, integrating emerging detection technologies with appropriate governance and monitoring systems can significantly enhance antibiotic residue surveillance in India's dairy value chain, supporting improved food safety, regulatory compliance, and public confidence in dairy products.

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