



Bio Vet Innovator Magazine

(Fueling The Future of Science...)

Volume 3 (Issue 1) JANUARY 2026



Popular Article

Magnetic Analytical Extraction for Detection of Antibiotic Residues in Food Samples

Bhuva Akash¹ and Manjali Rana²

1PhD scholar, Division of veterinary public health and epidemiology

2M.V.Sc., Division of Medicine,

ICAR-IVRI, Izatnagar,

Bareilly, U.P.-243122

***Corresponding Author:** akash1750patel@gmail.com

DOI: <https://doi.org/10.5281/zenodo.18275739>

Received: January 07, 2026

Published: January 15, 2026

© All rights are reserved by **Bhuva Akash**

Abstract:

Antibiotic residues in food of animal origin present a persistent threat to consumer safety and contribute to the emergence of antimicrobial resistance. Conventional sample-preparation techniques such as liquid-liquid extraction (LLE) and solid-phase extraction (SPE) are effective but are often time-consuming, solvent-intensive, and difficult to automate. Magnetic analytical extraction (MAE) — an umbrella term that includes magnetic solid-phase extraction (MSPE), magnetic solid-phase microextraction (MSPME), magnetic stir-bar sorptive extraction (MSBSE), magnetic matrix solid-phase dispersion (M-MSPD), and dispersive liquid-liquid microextraction (DLLME) variants — offers rapid, selective, and greener alternatives. MAE uses functionalized magnetic nanoparticles (MNPs) or magnetic matrices to selectively capture analytes from complex matrices; analytes are recovered by a small volume of eluent and the magnetic sorbent is separated with an external magnet, eliminating filtration or centrifugation. This review synthesizes the principles, sorbent chemistries, analytical coupling, and applications of MAE for antibiotic residue monitoring in milk, meat and eggs, discusses current limitations (matrix effects, selectivity, and multi-class analysis) and outlines plausible directions for future development including molecularly imprinted polymers (MIPs), magnetic ionic liquids, automation, and AI-guided method optimization.

Introduction:

The use of antibiotics in food-producing animals can lead to residues in edible tissues, milk and eggs that pose risks to human health and may select for resistant bacteria. Regulatory bodies such as the Codex Alimentarius Commission and national agencies (e.g., FSSAI) define maximum residue limits (MRLs) based on toxicological risk assessments; reliable analytical methods are therefore essential to enforce these limits and protect public health. Traditional extraction techniques (LLE, SPE, SPME, QuEChERS) coupled

with chromatographic or mass spectrometric detection remain widely used but often require extensive sample handling, large solvent volumes and lengthy processing times. Recently, magnetic analytical extraction (MAE) approaches have received considerable attention because they can reduce solvent use, simplify workflows, and be adapted for high-throughput or on-site analysis (El-Deen & Hussain, 2024). MAE leverages magnetic separation to rapidly isolate analytes from complex food matrices, improving speed and reducing risk of sample loss and contamination.

Principle of Magnetic Analytical Extraction (MAE):

MAE methods rely on magnetic nanoparticles (MNPs) or magnetic composites whose surfaces are functionalized with ligands that interact selectively with target analytes. In a typical workflow, the sample is brought into contact with the magnetic sorbent; analytes adsorb via hydrogen bonding, electrostatic interactions, hydrophobic forces or π - π stacking depending on sorbent chemistry. An external magnet collects the sorbent, the matrix is decanted, and analytes are eluted with a small volume of solvent for subsequent analysis (e.g., HPLC, LC-MS/MS, GC-MS). The high surface-to-volume ratio of nanoscale sorbents enhances binding capacity and kinetics; magnetic separation obviates centrifugation/filtration steps, shortening preparation time and enabling automation (Liu et al., 2017; Wang et al., 2018).

Major MAE Techniques and Their Characteristics:

- **Magnetic Solid-Phase Extraction (MSPE):**

MSPE uses dispersed MNP sorbents to extract analytes from liquid or homogenized solid samples. Advantages include fast kinetics, low solvent consumption and suitability for trace-level detection. MSPE is versatile and has been applied for a range of antibiotic classes; however, commercially available sorbents with broad selectivity are limited and some functionalized nanoparticles can be fragile or costly (Liu et al., 2017; Gao et al., 2023).

- **Magnetic Solid-Phase Microextraction (MSPME) & Magnetic Stir-Bar Sorptive Extraction (MSBSE):**

MSPME employs magnetic sorbent coatings in microextraction formats that require minimal solvent and sample volume, making them attractive for rapid screening. MSBSE uses PDMS-coated magnetic stir bars to preconcentrate nonpolar analytes; while effective for hydrophobic compounds, current coatings limit applicability across polar antibiotic classes and commercial availability is limited (Wang & Zhang, 2018).

- **Magnetic Matrix Solid-Phase Dispersion (M-MSPD):**

M-MSPD integrates the matrix disruption and sorption steps by blending samples with magnetic sorbent; magnetic separation replaces centrifugation, yielding faster processing and compatibility with fatty or lipophilic matrices. Magnetic ionic liquids (MILs) or magnetic deep eutectic solvents (MDESSs) have also been used to afford greener extraction media (Wang et al., 2022).

- **Dispersive Liquid-Liquid Microextraction (DLLME) Variants:**

Magnetic-assisted DLLME uses magnetic extraction solvents or magnetic dispersants to facilitate rapid phase separation. DLLME variants can offer very high preconcentration factors and are well suited for volatile or semi-volatile residues when coupled with GC-MS.

Magnetic Sorbents: Design, Functionalization and Binding Mechanisms:

A wide spectrum of sorbents has been reported: bare iron oxide cores, carbon-based magnetic composites, graphene-derived magnetic materials, porous magnetic carbons, and magnetic molecularly imprinted polymers (MIPs). Functional groups commonly used include amino ($-NH_2$), carboxyl ($-COOH$) and hydroxyl ($-OH$) moieties; π -conjugated supports can enable π - π interactions with aromatic antibiotics. Adsorption occurs via hydrogen bonding, electrostatic attraction, hydrophobic interaction and π - π stacking; optimizing surface chemistry to favor target classes while minimizing nonspecific binding is essential for selectivity (Gao et al., 2019; Wang & Zhang, 2018). MIPs provide template-directed cavities that greatly increase selectivity for a given antibiotic or class and show promise for multi-residue approaches when combined with layered analytical strategies (Liu et al., 2017; Gao et al., 2019).

Analytical Coupling and Applications in Food Matrices:

MAE is compatible with standard analytical detectors. Common workflows elute analytes into small solvent volumes that are injected into HPLC-UV, HPLC-FLD, LC-MS/MS or GC-MS platforms depending on analyte volatility and required sensitivity. Reports demonstrate successful application of MAE to milk, meat, and egg matrices, achieving low limits of detection and good recoveries for tetracyclines, fluoroquinolones, macrolides and nitroimidazoles among others (Liu et al., 2017; Gao et al., 2023; Wang et al., 2022). The improved preconcentration and reduced matrix carryover make MAE a valuable front-end for confirmatory residue analysis in regulatory laboratories and research settings.

Challenges and Limitations:

Despite the clear advantages of magnetic analytical extraction, several challenges continue to limit its routine adoption in regulatory and routine analytical laboratories. One of the major constraints is the pronounced matrix effect associated with complex food samples, where fats, proteins and carbohydrates may foul the magnetic sorbent surface or compete with target analytes for active binding sites, ultimately reducing extraction efficiency and compromising reproducibility. Achieving high selectivity, particularly for multi-class antibiotic analysis, also remains challenging, as the chemical diversity of antibiotics makes it difficult to design a single sorbent with uniformly high affinity; non-specific adsorption can further elevate background signals and affect quantitative accuracy. In addition, the long-term reusability and structural stability of functionalized magnetic nanoparticles can be problematic, as repeated extraction cycles may lead to surface degradation, ligand leaching or a gradual decline in adsorption capacity. Practical implementation is further constrained by issues related to scale and cost, since the large-scale,

low-cost synthesis of magnetic sorbents with consistent quality and performance is essential for routine surveillance programs. Finally, the lack of standardized methods, harmonized protocols and comprehensive interlaboratory validation studies hamper regulatory acceptance, underscoring the need for robust quality assurance and quality control frameworks before MAE can fully replace conventional extraction techniques. Addressing these limitations will require continued advances in sorbent engineering, deeper insight into adsorption thermodynamics in complex matrices, and the development of standardized and validated analytical workflows.

Future Perspectives:

Future perspectives in magnetic analytical extraction (MAE) highlight several research directions that can substantially enhance its applicability and impact in antibiotic residue monitoring. The development of magnetic molecularly imprinted polymers (MIPs) represents a major advancement, as these materials offer highly selective recognition sites tailored to specific antibiotics while retaining the advantages of rapid magnetic separation and sorbent reusability, making them particularly suitable for targeted residue analysis (Liu et al., 2017; Gao et al., 2019). In parallel, the emergence of magnetic ionic liquids and magnetic deep eutectic solvents provides greener extraction alternatives with tunable physicochemical properties, reduced volatility, and improved affinity toward diverse antibiotic classes, aligning MAE with principles of green analytical chemistry (Wang et al., 2022). Automation and the development of field-portable or cartridge-based extraction devices are also expected to expand MAE utility, as magnetic separation is inherently compatible with miniaturized and high-throughput systems designed for rapid, point-of-use screening. Furthermore, AI-assisted method development using machine learning models holds promise for predicting optimal sorbent compositions, extraction parameters and elution conditions, thereby minimizing empirical trial-and-error and accelerating method optimization. Finally, coupling MAE with biosensors, rapid immunoassays or ambient ionization mass spectrometry could enable near-real-time detection of antibiotic residues, supporting on-farm surveillance and early intervention strategies (El-Deen & Hussain, 2024). Collectively, these innovations are likely to drive the development of scalable, cost-effective and regulatory-compliant MAE-based surveillance systems without compromising analytical sensitivity or selectivity.

Conclusion:

Magnetic analytical extraction techniques represent a versatile, eco-friendly and efficient class of sample-preparation methods for antibiotic residue analysis in food. By combining rapid magnetic separation with tailored sorbent chemistries, MAE reduces solvent consumption and processing times while delivering high sensitivity. Technical challenges—particularly matrix effects and the need for broad-spectrum sorbents—remain, but ongoing developments in MIPs, magnetic ionic liquids, automated devices and AI-guided optimization promise to broaden applicability. With rigorous validation and

standardization, MAE has the potential to transform routine residue monitoring and support public-health safeguarding against antibiotic contamination and the spread of antimicrobial resistance.

Reference:

- El-Deen, A. K., & Hussain, C. M. (2024). Advances in magnetic analytical extraction techniques for detecting antibiotic residues in edible samples. *Food Chemistry*, 450:139381.
- Gao, W. R., Li, P., Qin, S., Huang, Z., Cao, Y. A., & Liu, X. (2019). A highly sensitive tetracycline sensor based on a combination of magnetic molecularly imprinted polymer nanoparticles and surface plasmon resonance detection. *Microchimica Acta*, 186(9).
- Gao, X. N., Lin, J. W., Li, T. N., Zhang, X. Q., Zeng, B. Z., Wang, X. L., & Zhao, F. Q. (2023). A magnetic porous carbon material derived from an MIL-101(Fe) complex for efficient magnetic solid phase extraction of fluoroquinolone antibiotics. *Analyst*, 148(17), 4203–4212.
- Liu, L. J., Yang, B. C., Zhang, F. F., & Liang, X. M. (2017). A magnetic restricted access material for rapid solid phase extraction of multiple macrolide antibiotics in honey. *Analytical Methods*, 9(20), 2990–2996.
- Liu, X. X., Xie, S. Y., Ni, T. T., Chen, D. M., Wang, X., Pan, Y. H., ... Yuan, Z. H. (2017). Magnetic solid-phase extraction based on carbon nanotubes for the determination of polyether antibiotic and s-triazine drug residues in animal food with LC–MS/MS. *Journal of Separation Science*, 40(11), 2416–2430.
- Wang, Q., & Zhang, L. (2018). Fabricated ultrathin magnetic nitrogen-doped graphene tube as efficient and recyclable adsorbent for highly sensitive simultaneous determination of three tetracyclines residues in milk samples. *Journal of Chromatography A*, 1568, 1–7.
- Wang, Y., Yuan, H. W., Wan, Y., & Zhang, L. (2022). Three-dimensional acanthosphere-like hierarchical Co@graphitic carbon for dispersive magnetic solid-phase extraction of nitroimidazole. *Journal of Chromatography A*, 1675.