Asian J. Med. Biol. Res. 2026, 12(2), 16-23; https://doi.org/10.3329/ajmbr.v12i2.88718

Asian Journal of
Medical and Biological Research
ISSN 2411-4472 (Print) 2412-5571 (Online)
https://www.ebupress.com/journal/ajmbr/

Editorial

Beyond antibiotics: charting a sustainable path for poultry production in the era of antimicrobial resistance

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Received: 05 March 2026/Accepted: 30 March 2026/Published: 07 April 2026

The global poultry industry stands at a critical crossroads. As we enter the third decade of the twenty-first century, the escalating crisis of antimicrobial resistance (AMR) has fundamentally challenged the foundations of modern livestock production. The widespread and often indiscriminate use of antibiotics in animal husbandry has created selective pressures that favor the survival and proliferation of multidrug-resistant (MDR) pathogens. This threatens not only animal health but also human health via the food chain and environmental contamination (Hoque *et al.*, 2021; Salam *et al.*, 2023; Baweja *et al*., 2025).

Our recent body of research, which includes investigations into antibiotic residues, phytogenic alternatives, and food safety protocols, highlights the depth of this challenge and the promising pathways forward. This editorial synthesizes findings from our laboratory's investigations over the past five years, contextualizing them within the broader global discourse on sustainable poultry production and offering a vision for future research and policy directions.

Over the past several years, our research group has systematically documented a troubling reality: the indiscriminate use of antibiotics in Bangladesh's poultry sector has led to widespread residue contamination in edible tissues. Our investigations have detected residues of commonly used antibiotics—ciprofloxacin, amoxicillin, enrofloxacin, colistin, and cephalexin—in poultry meat at levels exceeding the maximum residue limits (MRLs) established by international regulatory bodies (Islam *et al.*, 2021; Bhuiyan *et al.*, 2021; Hasan *et al.*, 2021; Anaruzzaman *et al.*, 2021).

In a comprehensive survey, ciprofloxacin residues were found in 47% of broiler meat samples collected from local markets in Bangladesh, with 23% exceeding the established MRL (Hasan *et al.*, 2025). Similarly, our investigation into amoxicillin revealed detectable residues in 38% of samples, with concentrations ranging from sub-therapeutic to pharmacologically active levels (Islam *et al.*, 2020). These findings align with broader regional patterns and identify systemic gaps in antibiotic stewardship across South Asian poultry production systems (Chowdhury *et al.*, 2021; Rafiq *et al.*, 2022).

Perhaps more concerning, our experimental studies in animal models have demonstrated that chronic exposure to these antibiotic residues above permissible levels induces measurable pathophysiological effects. Using murine models, we observed that continuous exposure to amoxicillin residues resulted in significant alterations in hematological parameters, including reduced lymphocyte counts and elevated heterophil-to-lymphocyte ratios, indicating compromised immune function (Islam and Islam, 2024). Similar investigations with cephalexin and ciprofloxacin revealed dose-dependent hepatotoxic and nephrotoxic effects, characterized by elevated serum liver enzymes and histopathological evidence of tissue damage (Islam *et al.*, 2024a; Islam *et al.*, 2024b).

These findings are not merely academic curiosities; they represent a direct threat to the "One Health" paradigm that links human health inextricably to animal health and environmental integrity (Kabir, 2025; Aslam and Aljasir, 2025). When consumers ingest poultry products containing sub-therapeutic levels of antibiotics, they are inadvertently exposed to selective pressures that favor the emergence of resistant pathogens in their own microbiomes. Other scientists have documented how such exposures contribute to the growing burden of resistant infections in human populations, particularly in low- and middle-income countries (LMICs) where regulatory oversight remains limited (Nicz *et al*., 2025; Elbehiry and Marzouk, 2025). The presence of antimicrobial residues in food products derived from animals in developing countries represents a significant public health concern (Hosain *et al.*, 2025).

Our surveys of informal poultry drug prescribers revealed a profound disconnect: while these practitioners play a pivotal role in Bangladesh's poultry health management, their knowledge regarding prudent antimicrobial use, withdrawal periods, and the consequences of residues remains alarmingly inadequate. We conducted cross-sectional interviews with 150 informal drug prescribers across five districts in Bangladesh and found that only 28% could correctly define antibiotic residues, while a mere 15% demonstrated awareness of established withdrawal periods for commonly used antibiotics (Sani *et al*., 2023).

This knowledge gap exists within a broader context of limited regulatory oversight and insufficient monitoring infrastructure—a scenario mirrored across many LMICs (Gandra *et al.*, 2020; Hoque *et al.*, 2020). The Bangladesh poultry sector, which has experienced remarkable growth over the past two decades, now produces over 300,000 metric tons of meat annually (Islam *et al.*, 2025). Yet, the regulatory framework governing antibiotic use has struggled to keep pace with this expansion. Our analysis of policy documents revealed fragmented oversight across multiple agencies, inadequate enforcement mechanisms, and limited capacity for routine residue monitoring (Islam, 2025).

The challenge, therefore, is not merely scientific but systemic. We face a complex web of factors: economic pressures on smallholder farmers, inadequate veterinary extension services, fragmented supply chains, and a lack of affordable, accessible alternatives to antibiotics. As I recently noted (Islam, 2025), addressing these interconnected issues requires a coordinated policy response that integrates education, regulation, and economic incentives within a comprehensive national action plan on AMR. The intricate relationship between climate change and AMR further complicates this landscape, necessitating integrated One Health solutions (Aslam and Aljasir, 2025).

The poultry production chain serves as a critical conduit for the transmission of antimicrobial-resistant foodborne pathogens from farm to fork (Elbehiry and Marzouk, 2025). Our research group has extensively documented the prevalence of major foodborne pathogens in poultry and associated environments in Bangladesh, including the first report of isolation of *Campylobacter* species from broiler meat sold in local markets, with significant resistance patterns to commonly used antimicrobials (Kabir *et al*., 2014). Subsequent studies revealed the widespread occurrence of *Campylobacter* spp. in dairy origin (Kabir *et al.*, 2018) and in diarrheal patients (Karmaker *et al*., 2018; Rahman *et al.*, 2021), indicating the zoonotic transmission potential.

The presence of multidrug-resistant *Campylobacter* spp. in poultry farms and live bird markets poses significant public health risks (Neogi *et al.*, 2020). Risk factors associated with *Campylobacter* colonization in farmed sheep have been identified (Nobi *et al*., 2024), while the occurrence of multidrug-resistant *Campylobacter* at duck farms highlights the importance of anthropogenic factors in transmission dynamics (Uddin *et al*., 2021).

Similarly, *Escherichia coli* has emerged as a significant concern in poultry production. The isolation of *E. coli* O157:H7 and non-O157:H7 from broiler meat in Mymensingh, Bangladesh, demonstrates alarming resistance profiles (Hossain *et al*., 2025). The occurrence of diarrheagenic and extended-spectrum beta-lactamase (ESBL)-producing *E. coli* on publicly shared common touch surfaces (Arif *et al.*, 2025) underscores the environmental dissemination of resistant pathogens. Further AMR patterns have been documented in *E. coli* isolated from goats and dairy cattle, respectively, demonstrating the widespread nature of this challenge across livestock species (Begum *et al*., 2016; Sobur *et al*., 2019).

Other foodborne pathogens have also been documented. *Salmonella gallinarum* has been found in small-scale commercial layer flocks (Haque *et al*., 2021), and *Salmonella* species have been detected in the washing and rinsing water of broilers in pluck shops (Ferdous *et al.*, 2013), highlighting contamination risks throughout the production chain. A further report documents the occurrence of *Clostridium perfringens* in layer flocks in Bangladesh, revealing significant AMR patterns (Arif *et al*., 2022). Additionally, the presence of *Aeromonas hydrophila* in broiler chickens (Sarker *et al.*, 2020) and *Vibrio cholerae* in dairy excreta (Eashmen *et al.*, 2021) further expands the spectrum of resistant pathogens in the food animal environment. Even fresh vegetables and betel leaves have been shown to harbor antimicrobial-resistant *Campylobacter jejuni* (Al-Mamun *et al.*, 2023) and *E. coli* (Islam *et al.*, 2024), demonstrating that contamination extends beyond animal products into the broader food system.

These findings collectively illustrate that AMR is not confined to clinical settings or animal production facilities but has permeated the entire food chain and environment (Lautan *et al.*, 2025; Tan and Xi, 2025). The silent crisis of antibiotic pollution in water systems and the spread of resistance represent emerging challenges that require effective mitigation strategies (Cave *et al.*, 2021; Tan and Xi, 2025).

Against this backdrop, our recent investigation into *Azadirachta indica* (neem) leaf extract presents a compelling sustainable alternative (Islam *et al.*, 2026). In this study, a chemically characterized neem leaf extract rich in limonoids, including azadirachtin, nimbin, nimbolide, gedunin, and salannin, demonstrated remarkable efficacy in broilers. Birds receiving the extract at a 0.05% concentration in drinking water achieved superior growth performance compared to controls, with final body weights comparable to or exceeding those of birds receiving the antibiotic danofloxacin or the metabolic booster butaphosphan.

The immunomodulatory effects were particularly striking. Neem-treated birds exhibited significantly increased lymphocyte counts and reduced heterophil-to-lymphocyte ratios—a well-established indicator of reduced stress and enhanced immune competence in poultry (Gross and Siegel, 1983). These findings align with earlier work that documented the immunostimulatory properties of neem bioactives and extend them by providing quantitative evidence of enhanced gut morphology, including significantly increased villus height and villus-height-to-crypt-depth ratios in the duodenum (Alzohairy, 2016).

Perhaps most significant from a food safety perspective, neem supplementation demonstrated hepatoprotective effects, with significantly lower serum levels of alanine aminotransferase (ALT) and aspartate aminotransferase (AST) compared to controls. This suggests that phytogenic compounds not only promote growth but also support organ health, potentially enhancing the overall physiological resilience of production animals (Karuppanan *et al*., 2014; Nakamura *et al*., 2022).

What makes this finding particularly significant is the multifunctional nature of phytogenic compounds. Unlike single-molecule antibiotics that exert narrow mechanisms of action, the complex mixture of bioactive compounds in neem works synergistically, exerting antimicrobial, anti-inflammatory, antioxidant, and immunomodulatory effects simultaneously (Subapriya and Nagini, 2005; Paul *et al*., 2020). This complexity not only enhances efficacy but also potentially reduces the evolutionary pressure for resistance development that plagues conventional antibiotics (Citarasu, 2010; Haq *et al*., 2025).

The convergence of our research findings points toward several critical directions for future investigation and policy development. First, we must move beyond binary comparisons of “antibiotics versus alternatives” toward integrated management strategies. The question is no longer whether phytogenics can replace antibiotics, but how they can be optimally integrated into comprehensive health management programs that include improved biosecurity, vaccination protocols, and precision nutrition. Our work on neem suggests that phytogenics may serve multiple functions simultaneously—as growth promoters, immunomodulators, and gut health enhancers—potentially reducing the need for multiple interventions (Lautan *et al*., 2025; Islam *et al*., 2026).

Second, standardization remains paramount. Our work with neem highlights that crude extracts yield inconsistent results (Islam *et al*., 2026). The future lies in chemically characterized, standardized phytogenic formulations where bioactive compound profiles are defined and reproducible. This requires investment in analytical infrastructure and quality control systems. Our development of thin-layer chromatography methods for antibiotic residue detection (Islam *et al*., 2021; Islam *et al*., 2024c) demonstrates that accessible analytical tools can support such standardization efforts.

Third, we urgently need longitudinal studies examining the economic viability of phytogenic-based production systems across different operational scales. Smallholder farmers, who constitute the backbone of poultry production in many LMICs (Mottet and Tempio, 2017), require evidence-based guidance on cost-benefit ratios and implementation strategies that suit their resource constraints. Our preliminary analysis suggests that neem extract supplementation at a 0.05% concentration offers favorable economics when production benefits are fully accounted (Islam *et al*., 2026), but large-scale field trials across diverse production contexts are needed to validate these findings.

Fourth, the potential for synergistic combinations warrants systematic exploration. Could standardized phytogenic extracts enhance the efficacy of vaccines? Might they reduce the therapeutic antibiotic doses required when treatment becomes necessary? Our preliminary findings on neem’s immunostimulatory effects (Islam *et al*., 2026) suggest such synergies are plausible and merit rigorous investigation. Recent work demonstrating neem’s efficacy against avian influenza virus in experimental chickens provides additional evidence for such synergies.

Fifth, and perhaps most ambitiously, we need to reconceptualize how we measure success in poultry production (Hegazy *et al*., 2023). For decades, the industry has prioritized narrow metrics—growth rate, feed conversion ratio, and profitability—while externalizing the costs of AMR and environmental contamination (Van der Most *et al*., 2011; Kogut, 2019). The emergence of antibiotic-free production systems offers an opportunity to develop more holistic assessment frameworks that account for food safety, animal welfare, environmental sustainability, and public health outcomes. Global surveillance of AMR in food animals using priority drugs maps (Zhao *et al*., 2024) represents an important step toward standardized monitoring.

Translating research findings into practice requires bridging traditionally siloed domains. Our recent work on thin-layer chromatography methods for residue detection (Islam *et al*., 2021; Islam *et al*., 2024c) demonstrates that accessible, cost-effective analytical tools can empower local monitoring efforts. Similarly, our studies on the pathophysiological impacts of chronic antibiotic exposure (Islam *et al*., 2024; Islam and Islam, 2024) provide the evidence base needed to inform regulatory standard-setting.

However, science alone is insufficient. Effective solutions require participatory approaches that engage farmers, veterinarians, extension agents, policymakers, and consumers. As highlighted by our colleague's work on informal drug prescribers (Sani *et al*., 2023), understanding local knowledge systems and practice contexts is essential for designing interventions that are both effective and adoptable. The development of context-appropriate educational materials, decision-support tools, and incentive structures must proceed in parallel with technological innovation.

The policy landscape is evolving. The European Union's ban on antibiotic growth promoters (Huyghebaert *et al*., 2011) has catalyzed similar regulatory actions globally. In Bangladesh, the National Action Plan on Antimicrobial Resistance (2017-2022) established a framework for coordinated action, but implementation has been hampered by resource constraints and coordination challenges (Hoque *et al*., 2020; Islam, 2025). Strengthening this policy framework requires sustained investment in surveillance infrastructure, regulatory enforcement, and extension services. The role of public health veterinarians in advancing One Health approaches is critical (Kabir, 2025).

As we look toward the future, I propose the following priorities for our research community, including establish collaborative networks for phytogenic research that enable the standardization of extraction methods, compound identification, and efficacy testing across different geographical contexts and production systems. Such networks should facilitate the sharing of reference materials, analytical protocols, and data, accelerating the development of evidence-based phytogenic formulations (Lautan *et al*., 2025; Haq *et al*., 2025). Develop integrated surveillance systems that simultaneously monitor antibiotic residues, resistance patterns, and the adoption of alternative strategies, enabling evidence-based policy refinement. Our work on detection methods (Islam *et al*., 2021; Hasan *et al*., 2025) provides a foundation for such systems, but scaling them to national and regional levels requires sustained investment and inter-sectoral collaboration. The global surveillance framework proposed offers a valuable model (Zhao *et al*., 2024). Invest in translational research that bridges laboratory findings to on-farm applications, including the development of user-friendly decision-support tools for farmers and prescribers. This includes research on optimal delivery methods (feed vs. water), timing of supplementation, and integration with existing management practices (Paul *et al*., 2020; Islam *et al*., 2026). Expand the evidence base on phytogenic safety, including long-term studies, potential interactions with other feed components, and residue profiles in animal products. While neem has a long history of traditional use (Subapriya and Nagini, 2005), modern production systems require rigorous safety assessments under controlled conditions. Engage with the social sciences to better understand the behavioral, economic, and institutional factors that shape antimicrobial use practices, ensuring that technological solutions align with human realities. Our work on knowledge gaps among drug prescribers (Sani *et al*., 2023) represents an initial step; deeper ethnographic and economic analyses are needed to inform effective interventions. Strengthen regulatory frameworks for antibiotic use and residue monitoring in LMICs, drawing on lessons from successful interventions globally. This includes investment in laboratory capacity, training of inspectors, and the development of traceability systems that can support responsible antibiotic stewardship (Gandra *et al*., 2020; Chowdhury *et al*., 2021).

The challenge of AMR in animal agriculture is not insurmountable, but it requires a fundamental shift in our approach to production, health management, and food safety. Our research on neem leaf extract demonstrates that nature offers sophisticated solutions—if we are willing to invest in understanding, standardizing, and implementing them thoughtfully. The multi-functional benefits of phytogenic compounds—enhancing growth, immunity, gut health, and organ function simultaneously—represent a paradigm shift from the reductionist approach of single-molecule antibiotics.

The path forward demands humility regarding the complexity of biological systems, rigorous science to guide our interventions, and collaboration across disciplines and sectors. As we continue this work, we must remain mindful that our ultimate responsibility extends beyond academic publication to the practical goal of ensuring safe, nutritious, and sustainably produced food for a growing global population.
The antibiotic era in animal agriculture is coming to an end. Our task now is to ensure that what follows is built on a foundation of scientific evidence, economic viability, and a genuine commitment to the "One Health" principles that recognize our shared fate with the animals we raise and the environment we inhabit. The transition will not be easy, but the consequences of inaction—a post-antibiotic era where common infections become untreatable—are far more dire. Let us, therefore, embrace this challenge with the urgency it demands and the creativity it deserves.

Ethical approval and informed consent
Not applicable.

Data availability
Not applicable.

Conflict of interest
None to declare.

Author's contribution
Conceptualization, formal analysis, writing-original draft preparation, review and editing: Md. Shafiqul Islam. The author has read and approved the final version of the published editorial.

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