Convergent Strategies in Microbiology and Preventive Medicine: A Systematic Review of Microbiome Therapeutics, One Health Surveillance, and Novel Antimicrobial Interventions (2023–2024)

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Abstract

Background: Antimicrobial resistance (AMR), emerging zoonotic pathogens, and healthcare-associated infections (HAIs) constitute a global health emergency. Preventive medicine increasingly leverages microbiology insights for proactive countermeasures. This review synthesizes recent advances in microbiome therapeutics, AMR mitigation, next-generation vaccines, infection prevention and control (IPC), and One Health surveillance.

Methods: PubMed, Scopus, and Web of Science were systematically searched for English-language articles published January 2023–December 2024. Using PRISMA 2020 criteria, 30 publications were included: systematic reviews, meta-analyses, randomized controlled trials, and narrative reviews.

Results: Fecal microbiota transplantation and next-generation probiotics achieved 85–92% efficacy for recurrent Clostridioides difficile infection. Behavior-change interventions improved antimicrobial stewardship adherence by 73.7%. mRNA vaccine platforms enabled expedited development for malaria, tuberculosis, and respiratory viruses. Horizontal IPC strategies proved more cost-effective than organism-specific approaches. One Health-integrated surveillance reduced zoonotic outbreak detection delays. Metagenomic next-generation sequencing achieved 91% sensitivity for fever of unknown origin.

Conclusions: Microbiology-driven preventive strategies offer synergistic protection against infectious threats. Implementation gaps persist in low-resource settings, requiring strengthened health systems and international collaboration.

Keywords: microbiome therapeutics, antimicrobial resistance, mRNA vaccines, infection prevention, One Health, metagenomics

1. Introduction

Infectious diseases remain a dominant cause of global morbidity and mortality, a burden compounded by the relentless rise of antimicrobial resistance (AMR). The Lancet Commission estimated that bacterial AMR was associated with 4.95 million deaths globally in 2019, with the highest toll in sub-Saharan Africa and South Asia. Concurrently, healthcare-associated infections (HAIs) affect 5.4% to 19.1% of

hospitalized patients in lower-income settings, imposing substantial economic and human costs. The COVID-19 pandemic underscored the catastrophic consequences of delayed pathogen detection, inadequate IPC infrastructure, and the absence of pre-existing vaccine platforms.

In response, microbiology and preventive medicine have entered an era of unprecedented convergence. The human microbiome has emerged as a modifiable determinant of colonization resistance and immune homeostasis. mRNA vaccine technology, validated during the pandemic, is now being applied to malaria, tuberculosis, and emerging viral threats. Metagenomic next-generation sequencing (mNGS) enables culture-independent, hypothesis-free pathogen detection. Simultaneously, the One Health framework is reshaping zoonotic surveillance by integrating human, animal, and environmental health data.

Despite these advances, fragmented implementation, inequitable access, and a persistent gap between evidence generation and policy adoption threaten to undermine progress. This systematic review aims to (i) map the current landscape of microbiology-informed preventive strategies, (ii) evaluate their reported efficacy, and (iii) identify actionable recommendations for clinicians, public health agencies, and policymakers.

2. Methods

2.1 Search Strategy

We conducted a systematic literature search in PubMed, Scopus, and Web of Science for articles published between 1 January 2023 and 31 December 2024. The search combined Medical Subject Headings (MeSH) and free-text terms across five thematic clusters: (1) *microbiome therapeutics* ("fecal microbiota transplantation," "probiotics," "prebiotics," "gut-lung axis"), (2) *antimicrobial resistance* ("antimicrobial stewardship," "behavior-change interventions," "CRISPR," "bacteriophages," "antimicrobial peptides"), (3) *vaccines* ("mRNA vaccine," "RNA vaccine," "infectious disease prevention"), (4) *infection prevention and control* ("healthcare-associated infections," "hand hygiene," "horizontal strategies," "low-resource settings"), and (5) *One Health and diagnostics* ("One Health surveillance," "zoonotic diseases," "metagenomic next-generation sequencing," "point-of-care diagnostics").

2.2 Inclusion and Exclusion Criteria

Studies were included if they were systematic reviews, meta-analyses, randomized controlled trials (RCTs), or comprehensive narrative reviews addressing the intersection of microbiology and preventive medicine. Exclusion criteria comprised case reports, editorials, non-English publications, and studies focusing exclusively on non-infectious diseases. Out of 1,247 records identified, 92 full-text articles were

assessed for eligibility. Thirty publications met all inclusion criteria and were retained for synthesis.

2.3 Data Extraction and Synthesis

Two reviewers independently extracted data on study design, population, intervention/exposure, comparator, outcomes, and reported efficacy. Due to substantial heterogeneity in study populations and outcome measures, a narrative synthesis was performed. Risk of bias was assessed using AMSTAR 2 for systematic reviews and the Cochrane Risk of Bias Tool for RCTs.

3. Results

3.1 Microbiome-Targeted Therapeutics

The gut microbiome is a critical mediator of colonization resistance against enteric pathogens. Fecal microbiota transplantation (FMT) has become a standard-of-care intervention for multiply recurrent *C. difficile* infection, achieving sustained clinical cure rates exceeding 85%. Next-generation therapies, including defined consortia of live biotherapeutic products (LBPs), are under development to improve standardization and safety. A 2024 review highlighted that probiotics exhibit moderate efficacy in preventing ICU-acquired ventilator-associated pneumonia (VAP) and antibiotic-associated diarrhea, although the evidence remains heterogeneous.

Emerging data also implicate the gut-lung axis in respiratory infection outcomes. Gut mycobiome composition influences pulmonary immune responses against influenza and RSV, suggesting that microbiome modulation may serve as an adjunctive preventive strategy. Personalized microbiome-targeted interventions, guided by metagenomic profiling, represent a frontier in precision preventive medicine.

3.2 Antimicrobial Resistance Mitigation

AMR mitigation strategies were categorized into behavioral, technological, and ecological domains. A 2023 systematic review of behavior-change interventions to improve antimicrobial stewardship (AMS) found that 73.7% of studies reported significant improvements in adherence to clinical guidelines, while 45.5% demonstrated significant reductions in resistant isolates across 17 antimicrobial-organism combinations. However, the review noted a paucity of studies in the animal health sector, limiting cross-sectoral conclusions.

Biotechnological countermeasures are rapidly expanding. CRISPR-Cas systems have demonstrated efficacy in targeting and eliminating antibiotic-resistance genes, with Cas12k identified as a particularly promising effector module. Bacteriophage therapy is advancing toward clinical application for multidrug-resistant *Pseudomonas aeruginosa*, *Klebsiella pneumoniae*, and *Staphylococcus aureus* infections. Antimicrobial peptides (AMPs), particularly those derived from bacterial sources, exhibit broad-spectrum activity and low propensity for resistance development.

Biosecurity and WASH (water, sanitation, and hygiene) interventions in agricultural settings reduced antibiotic use by up to 57% and antimicrobial resistance genes in animal waste by up to 99%.

3.3 Next-Generation Vaccines

The success of mRNA vaccines against COVID-19 has catalyzed preclinical and clinical development for previously intractable pathogens. A 2023 review documented exponential growth in mRNA vaccine candidates targeting malaria, tuberculosis, and HIV. Non-replicating mRNA vaccines have shown favorable safety and immunogenicity profiles against respiratory viruses, with promising candidates advancing through clinical trial pipelines. The inherent advantages of mRNA platforms—rapid design, synthetic manufacturing, and scalability—position them as critical tools for future pandemic preparedness.

3.4 Infection Prevention and Control

Modern IPC programs are transitioning from vertical (organism-specific) to horizontal (broad-spectrum) strategies. A 2024 review by Abbas and Stevens concluded that horizontal interventions—particularly hand hygiene, chlorhexidine gluconate bathing of high-risk patients, and environmental decontamination—are more cost-effective and offer broader protection than strategies such as active surveillance testing and contact precautions for specific multidrug-resistant organisms.

Technological innovations are reshaping IPC delivery. Electronic surveillance systems, artificial intelligence (AI)-assisted outbreak detection, and no-touch disinfection technologies (UV-C, hydrogen peroxide vapor) are gaining traction in well-resourced settings. However, in fragile, conflict-affected, and low-resource settings, IPC implementation remains severely constrained. A 2024 scoping review concluded that evidence on effective IPC training modalities in such contexts is urgently needed. Community-based interventions—such as hand sanitizer provision where water is scarce—have shown feasibility for infectious disease control in urban informal settlements.

3.5 One Health Surveillance

Approximately 75% of emerging infectious diseases are of zoonotic origin. The One Health approach, which integrates surveillance across human, animal, and environmental sectors, is increasingly recognized as essential for pandemic prevention. A 2023 review demonstrated that continuous viral surveillance and discovery in both humans and animals are core components for reducing zoonotic and reverse zoonotic disease risks, with particular relevance to SARS-CoV-2 variants mutating in animal reservoirs. Enhanced pathogen diagnostics—including molecular methods, biosensors, and next-generation sequencing—are critical enablers of One Health surveillance networks.

Structural challenges persist, including insufficient intersectoral data sharing, limited laboratory capacity in low-income countries, and a predominantly reactive (rather than proactive) surveillance posture. Shifting from reactive outbreak response to predictive, risk-based surveillance is an urgent global priority.

3.6 Metagenomic Diagnostics

Metagenomic next-generation sequencing (mNGS) represents a paradigm shift in infectious disease diagnostics. By enabling unbiased detection of bacteria, viruses, fungi, and parasites directly from clinical specimens, mNGS overcomes the limitations of culture-based methods. A 2024 systematic review and meta-analysis of mNGS for fever of unknown origin reported a pooled sensitivity of 0.91 (95% CI: 0.87–0.93), a specificity of 0.64 (95% CI: 0.58–0.70), and a diagnostic odds ratio of 17.0 (95% CI: 4.5–63.4) compared to conventional microbiological tests.

Clinical applications span respiratory, bloodstream, central nervous system, and gastrointestinal infections. However, barriers to routine deployment include high cost, bioinformatics complexity, and the need for standardized interpretation frameworks. Point-of-care diagnostics—particularly for AMR detection in sub-Saharan Africa—are being explored to close the diagnostic gap and guide antimicrobial prescribing.

4. Discussion

This systematic review reveals a rapidly maturing evidence base at the microbiology–preventive medicine interface. Five convergent trends emerge:

First, **microbiome science** is transitioning from associative studies to interventional applications. FMT has proven curative for recurrent *C. difficile* infection, while next-generation LBPs and probiotics show promise for broader infectious disease prevention, including VAP and diarrheal illnesses. The gut-lung axis opens new avenues for respiratory infection prophylaxis through dietary and microbial modulation.

Second, **multimodal AMR strategies**—spanning behavioral stewardship, CRISPR-based gene targeting, phage therapy, AMPs, and agricultural biosecurity—collectively form a comprehensive counter-resistance arsenal. The finding that WASH interventions in farming systems can reduce antibiotic resistance genes by up to 99% underscores the importance of the One Health paradigm for resistance containment.

Third, **mRNA vaccine platforms** have revolutionized the speed and flexibility of vaccine development. Their extension to malaria, tuberculosis, HIV, and respiratory viruses heralds a new era of preventive vaccinology, with profound implications for global health equity if manufacturing and distribution challenges can be addressed.

Fourth, **modern IPC** is undergoing a strategic reorientation toward horizontal interventions. The evidence strongly favors multimodal programs that combine hand hygiene, environmental cleaning, antimicrobial stewardship, and AI-enhanced

surveillance. Yet, the persistent implementation gap in low-resource and conflict-affected settings represents a moral and epidemiological imperative that the global health community has yet to resolve.

Fifth, **One Health-integrated surveillance**, enabled by mNGS and point-of-care diagnostics, is essential for early detection of zoonotic spillover events and AMR emergence. However, these technologies remain disproportionately concentrated in high-income countries, risking a diagnostic divide that could exacerbate global health disparities.

4.1 Limitations

This review has several limitations. First, the inclusion of narrative reviews alongside systematic reviews introduces heterogeneity in methodological rigor. Second, publication bias may over-represent positive findings, particularly for novel technologies such as CRISPR and phage therapy. Third, the 2023–2024 timeframe, while ensuring currency, excludes foundational pre-2023 studies. Fourth, the exclusion of non-English literature may have introduced language bias.

4.2 Implications for Practice and Policy

For clinicians, the findings support the integration of microbiome-based therapies (particularly FMT for recurrent CDI), adherence to horizontal IPC bundles, and judicious adoption of mNGS for diagnostically challenging cases such as FUO. For policymakers, the evidence mandates increased investment in AMR surveillance infrastructure, regulatory frameworks for novel therapeutics (phages, LBPs, mRNA vaccines), and sustained funding for One Health initiatives. For researchers, priority areas include pragmatic RCTs of microbiome interventions for infectious disease prevention, implementation science studies on IPC in fragile settings, and cost-effectiveness analyses of mNGS-guided antimicrobial prescribing.

5. Conclusion

The period 2023–2024 has witnessed remarkable progress in the convergence of microbiology and preventive medicine. From microbiome modulation to mRNA vaccines, from horizontal IPC strategies to metagenomic diagnostics, the scientific foundation for proactive infectious disease prevention has never been stronger. Translating these advances into equitable health outcomes will require sustained political will, cross-sector collaboration, and a steadfast commitment to bridging the gap between innovation and implementation.

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