Biotechnology-Based Detection of Food Contaminants: Implications for Food Safety, Agricultural Trade, and Economic Loss Reduction

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Abstract

Food contamination by microbial pathogens, mycotoxins, pesticide residues, heavy metals, and adulterants causes an estimated several hundred million episodes of foodborne illness annually, kills hundreds of thousands of people each year, and imposes economic losses on producers, processors, and trading nations that are measured in tens of billions of dollars. Detection is the hinge of every food-safety system: hazards that are found early and cheaply are managed, while hazards that are found late, or not at all, become public health events, trade rejections, and destroyed livelihoods. Conventional analytical methods (culture-based microbiology, chromatography, mass spectrometry) are accurate but slow, centralized, expensive, and poorly matched to the scale and geography of risk in modern supply chains. This review synthesizes the biotechnology-based detection platforms that have emerged over the past decade, polymerase chain reaction and isothermal nucleic-acid amplification, immunoassay and lateral-flow formats, aptamer-based and electrochemical biosensors, CRISPR-based nucleic-acid detection, and omics- and data-driven screening, and evaluates their performance, costs, and deployment requirements across contaminant classes. It then traces the consequences of detection capability (and its absence) through three connected domains: domestic food safety and public health; international agricultural trade, where sanitary and phytosanitary measures, import alerts, and rejections redistribute income between and within countries; and farm- and firm-level economic losses from recalls, destroyed stock, and lost market access. The synthesis shows that biotechnology-based detection shifts the economics of food safety from ex-post catastrophe management to ex-ante risk control, with the largest marginal returns in the testing gaps of developing-country production and export systems. Barriers, laboratory infrastructure, quality assurance, regulatory recognition, and cost at the point of sale, are analyzed, and a phased adoption pathway is proposed linking portable platforms, sentinel surveillance networks, and trade-facing accreditation.

Keywords: food contaminants; biosensors; mycotoxins; pathogens; food safety; sanitary and phytosanitary measures; agricultural trade; economic losses; developing countries

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1. Introduction

1.1. The global burden of food contamination

Unsafe food is one of the largest under-weighted burdens in global health and agricultural economics. The World Health Organization's landmark estimates attribute to 31 hazards, principally diarrheal disease agents, helminths, and toxins, an estimated 600 million episodes of foodborne illness and 420,000 deaths each year [1], with children under five bearing a disproportionate share; the World Bank has valued the associated productivity and economic loss-

es at on the order of US$95–110 billion annually in low- and middle-income countries alone, excluding the trade effects [2]. Beyond acute illness, chronic exposure to contaminants, aflatoxins and other mycotoxins, heavy metals such as cadmium and lead, pesticide residues, contributes to cancer, developmental impairment, and organ damage whose costs accrue silently across decades. For agriculture, the burden registers differently but no less heavily: contaminated lots are destroyed or diverted, consignments are rejected at import borders, firms are delisted from buyer registries, and entire national industries, groundnuts, spices, aquaculture, horticulture, have suffered multi-year market exclusion after contaminant events [3]. Studies of informal e-waste and automobile-recycling sites have assessed polychlorinated biphenyls in soils and their health risks [4], [5], and machine learning and AI frameworks have been proposed for linking environmental pollutant exposure to cancer risk and biochemical damage [6], [7].

1.2. Why detection is the hinge

Food-safety management has three stations: prevention (good agricultural and hygienic practice, HACCP-style process control), detection (testing and surveillance), and response (recalls, trade measures, clinical care). Of the three, detection is the hinge because every other station depends on it. Prevention protocols are only as good as the monitoring that verifies them; response is only as fast as the diagnostic that identifies the hazard. A contaminant detected at the field or storehouse stage costs a fraction of one detected in a processed shipment abroad: the difference is not only the value of the food itself but the destination market's institutional reaction, import alerts, intensified inspection rates, and reputational discounting that outlast the event by years. Detection capability, its speed, its cost, its sensitivity, and above all its geographic placement in the supply chain, is therefore a first-order economic variable in agricultural trade, not a laboratory technicality [8].

1.3. The biotechnology turn

The last two decades have transformed what detection can be. Nucleic-acid amplification made pathogen identification fast and specific without culture. Immunoassays made toxin and residue screening cheap enough for field use. Biosensors, devices coupling a biological recognition element to a physical transducer, brought continuous, on-site, increasingly smartphone-integrated measurement into the feasible set. Most recently, CRISPR-derived nucleic-acid detection has compressed the equipment requirements of molecular diagnostics to a heat block and a lateral-flow readout, and machine-learning models applied to spectral and genomic data have begun to automate contaminant recognition. These platforms do not merely accelerate conventional testing; they change where testing can happen and therefore change the economics of the entire safety system. This review's purpose is to organize that transformation and trace its consequences for food safety, trade, and economic loss [9].

1.4. Objectives and structure

The review pursues five objectives: (i) to map contaminant classes and the conventional detection landscape and its limits; (ii) to classify and compare biotechnology-based detection platforms; (iii) to assess their implications for domestic food safety and public health; (iv) to assess their implications for international agricultural trade under sanitary and phytosanitary (SPS) disciplines; and (v) to develop the economics of detection-led loss reduction, including barriers and an adoption pathway for developing-country systems. Section 1.5 treats contaminants and conventional methods; Sections 3.1 to 3.3 the platforms and their implementation; Sections 4.1 and 4.2 the domestic and trade consequences; Section 4.3 the adoption barriers and pathway; Sections 4.4 to 4.7 the trade economics, quality infrastructure, frontier and financing analyses; Sections 2.1 to 2.3 the loss, surveillance and risk frameworks; Section 3.4 the cost–benefit illustrations; Section 5.1 gives future directions; and Section 5 concludes.

Recent peer-reviewed evidence on Biosensor classification and microbiological applications: A food science and packaging perspective reinforces this assessment [10].

1.5. Contaminants and the conventional detection landscape

1.5.1. Contaminant classes

Five classes account for most of the burden and most of the trade friction. Microbial pathogens, *Salmonella*, *Listeria monocytogenes*, pathogenic *Escherichia coli*, *Campylobacter*, *and Vibrio* species dominate acute illness and drive the strictest import controls, notably the zero-tolerance standards applied to *Listeria* in ready-to-eat foods and to *Salmonella* in poultry and seed consignments. Mycotoxins, aflatoxins, fumonisins, deoxynivalenol, ochratoxin A, zearalenone, are fungal metabolites of field and storage molds; aflatoxin B1 is among the most potent liver carcinogens known, and its regulatory limits in the European Union (single-digit parts per billion for many foods) are among the binding constraints on African and Asian

groundnut, maize, and spice exports, with documented aflatoxin prevalence in feed markets illustrating the surveillance gap that depot-level screening addresses [11]. **Pesticide residues** are governed by maximum residue limits (MRLs) that vary by jurisdiction, and their violation, often from misuse or from divergence between trading partners' standards, is a leading cause of consignment rejection. **Heavy metals** (lead, cadmium, arsenic, mercury) enter from soil, water, and processing equipment, with chronic-toxicity thresholds driving standards. **Adulterants and fraud markers**, from melamine in dairy to economically motivated species substitution, are detected increasingly through the same biotechnology toolkit, with authenticity becoming a formal element of food-safety regulation [12]. Neonicotinoid pesticide residues in African agriculture [13] and per- and polyfluoroalkyl substances in Nigeria [14] illustrate the residue classes that detection must cover.

1.5.2. Conventional methods and their limits

The reference methods of food-safety laboratories are culture-based enumeration for pathogens; chromatographic separation with ultraviolet, fluorescence, or mass-spectrometric detection (HPLC, GC-MS, LC-MS/MS) for toxins, residues, and adulterants; and atomic absorption or inductively coupled plasma spectrometry for metals. These methods are accurate, standardizable, and internationally recognized, and they are slow (culture can require days of enrichment), expensive (capital equipment in the hundreds of thousands of dollars, skilled analysts, controlled environments), and centralized (a national reference laboratory serving an entire production geography). Their structural consequence is a temporal and spatial mismatch with risk: contamination events are concentrated in fields, stores, wet markets, and small processing units, while reference testing happens days later, hundreds of kilometers away. Rapid, cheap, and decentralized platforms exist alongside reference methods as screening tools, but the screening-to-confirmation gap, where a rapid test is positive and confirmation takes days, is itself an economic event, halting shipments and sales. The biotechnology platforms reviewed next are best understood as collapsing the speed, cost, and distance penalties of the reference system, while remaining legally dependent on it for confirmation and accreditation [15]. Rapid analytical techniques for food contaminants, with their applications and limitations, have been reviewed [16].

2. METHODS

2.1. Economic loss reduction: a framework

2.1.1. Where the losses live

Economic losses from food contamination concentrate in four accounts. **Direct product losses**: destroyed or diverted contaminated stock, from farm lots to processed shipments [17]. **Compliance and trade costs**: testing, certification, delays, rejections, and the capital costs of intensified inspection. **Health and productivity costs**: illness, mortality, and long-run chronic disease burdens, borne by households and health systems. **Reputational and market losses**: price discounts, lost contracts, and market exclusion that persist beyond the hazard event. The distribution of these accounts across the supply chain determines incentives: farmers bear direct losses and health costs; traders and exporters bear trade costs; consumers bear health costs; importing-country regulators set the enforcement parameters that price the externalities. Detection technology redistributes these costs by making hazard information available earlier and cheaper at each node, and experimental economics confirms that loss-reduction investments can generate measurable returns [18].

2.1.2. The value of a test: an economic identity

The economic value of deploying a detection platform at a supply-chain node can be expressed as the expected loss avoided, net of testing cost:

$$V = \sum_c p_c \times L_c(n_{\text{before}} - n_{\text{after}}) - C_{\text{test}} \qquad (1)$$

where p_c is the prevalence of contaminant class c, L_c the loss per contaminated unit under a testing regime with n detection events per unit time, and C_{test} the platform's cost per decision. The identity makes the economics legible: value rises with prevalence (testing pays most where risk is high), with the loss magnitude per event (perishables, high-value exports, health-critical foods), and with the platform's speed and sensitivity (earlier and truer detection converts catastrophic losses into cheap diversions). It also exposes the equity problem: private actors test when their expected private loss is high, but the largest aggregate losses, chronic public-health burdens, national reputation, are diffuse externalities that private testing does not capture, which is the economic rationale for public financing of surveillance infrastructure [3].

2.1.3. Loss reduction in practice

Applying the framework to documented contaminant epi-

sodes yields consistent patterns. For mycotoxins in export crops, depot-level screening plus pre-shipment confirmation routinely converts border rejections into internal diversion, with per-consignment savings that dwarf per-test costs by two to three orders of magnitude; the binding constraints become logistics of diversion and market access for safe uses, not detection. For pathogens in perishable chains, hour-scale molecular detection shortens hold times and reduces the batch sizes exposed to a positive result, cutting waste per event. For residues, screening at pesticide-purchase points and pre-harvest intervals addresses the misuse at its origin, which border testing can only punish. In every case, the platform's economic contribution is the conversion of a large, late, public loss into a small, early, private one, the core mechanism by which biotechnology-based detection reduces economic losses in agricultural systems [19].

2.2. Surveillance Epidemiology and Risk-Based Targeting

2.2.1. From testing to surveillance: the epidemiological layer

Testing becomes surveillance when results accumulate into structured evidence: prevalence estimates by commodity, geography, season, and actor type, tracked over time. The epidemiological layer converts individual test results into the population parameters that program design needs, the prevalence terms of the value-of-testing identity, and its methodological requirements are specific: sampling frames drawn from the actual flow of the commodity chain, sample sizes powered to the decision rather than to tradition, and bias control where sampling follows convenience rather than frame. The reviewed surveillance literature in food-safety and adjacent one-health fields converges on the same design essentials, and the framework's contribution is the linkage: the sentinel network of Section 4.3.2 is the sampling infrastructure, the platforms of Section 3.1 are the measurement infrastructure, and the epidemiology is the inference layer that makes either meaningful [4], [20], [21].

2.2.2. Risk-based targeting: allocating a fixed testing budget

Every surveillance system operates under a fixed testing budget, and the allocation question, which commodities, nodes, and seasons to test, is answerable with the framework's own parameters. Risk-based targeting weights sampling by expected loss: prevalence (from surveillance history), loss magnitude per event (value density, health burden, trade exposure), and detection value (the loss reduction an early finding enables). The formal result is the classical risk-prioritization structure of inspection theory, and its practical content here is concrete: testing concentrates on high-value perishables in warm seasons, on commodities with violation history, on aggregation nodes whose volumes concentrate risk, and on export pre-shipment where the rejection externality is largest. The reviewed applications of risk-based inspection in adjacent regulatory domains document the efficiency gains over uniform sampling, several-fold more detections per unit budget, and the equity caution: uniform sampling'srandomness is sometimes its political protection, so risk-based systems should publish their criteria to sustain legitimacy [6], [22].

2.2.3. Data analytics and the learning surveillance system

Surveillance data supports a learning layer beyond static targeting: trend detection (seasonal and annual prevalence movement), anomaly detection (lots or nodes whose results depart from history), and source attribution (genomic and supply-chain linkage of pathogen findings). The analytical literature, machine-learning classification, spatial statistics, and genomic epidemiology, supplies the methods, and the reviewed food-safety applications are advancing on all three [6], [7], [22]. The framework's contribution is the integration discipline: analytics without the node-structured chain model cannot translate a detected anomaly into an actionable intervention point, and the chain model without analytics cannot find the anomaly in the first place. The surveillance systems that matter are jointly designed, platforms, chain model, and analytics as one architecture, and the design principle is the same one this review has applied throughout: every layer is chosen for the decision it enables, not for the sophistication it displays [20], [23].

2.2.4. Cost-effectiveness thresholds and the investment case

The extended economics permits the investment case to be stated as a threshold. Surveillance investment is justified when the expected value of information, the loss reduction that earlier and better detection enables, summed over health, trade, and product-loss accounts, exceeds the system's annualized cost. The reviewed components of that expected value are now quantifiable in principle: prevalence and loss magnitudes from the surveillance literature, detection-value parameters from program evalua-

tions, and system costs from the accreditation and platform economics of this review. The honest state of the art is that the threshold is calculable for specific chains with specific data and has rarely been calculated in full for national systems, the measurement agenda's final item, and the one whose completion would most change the financing conversation, because the financing argument for detection infrastructure has always been plausible and is now, chain by chain, becoming computable [2], [18].

2.3. Risk Assessment: Prioritizing the Hazard Portfolio

2.3.1. Risk ranking methodology for a bounded system

A national detection system faces a hazard portfolio larger than any budget can test, and the risk-ranking discipline that inspection theory supplies converts the constraint into method. Each hazard-commodity pair is scored on the risk attributes the framework's loss identity implies: prevalence (surveillance history), severity (health burden per event, from the burden literature), trade exposure (export volume at risk and market sensitivity), and detectability (the platform coverage and cost of finding it). The scoring's output is a ranked portfolio whose top decile receives the system's first capacity, and whose maintenance is a published, revisable method rather than a fixed list, the transparency that sustains the legitimacy risk-based systems require. The reviewed risk-prioritization applications in food-safety and adjacent regulatory domains document the method's efficiency gains and its principal design caution: scores are instruments for allocation, not verdicts on hazards, and low-ranked hazards retain baseline surveillance because portfolio rank is a budget statement, not a safety claim [2], [6], [20].

2.3.2. Emerging-hazard watch: the portfolio's dynamic edge

The hazard portfolio's edge is dynamic, contaminants whose importance is rising faster than their surveillance history, and the watchlist discipline manages it. The candidates this review's extended contaminant analysis identifies: antimicrobial-resistance organisms in animal-source chains, whose detection platforms the biosensor literature is advancing; microplastic and associated-pathogen vectors in the one-health frame; mycotoxin co-occurrence under changing climate envelopes, which shifts prevalence geographically; and the authenticity-fraud families whose economics migrate with price spreads. The watchlist's operating rule: emerging hazards receive scout-level surveillance, cheap, broad, deliberately sensitive, whose positive findings graduate them onto the ranked portfolio with the full methodological apparatus. The reviewed emerging-risk literature in adjacent environmental and health domains supplies the scout-tier design, and its fit to the platform families this review covers is direct: the same lateral-flow, isothermal, and spectral infrastructure that serves the ranked portfolio serves the watch [5], [20], [24], [25].

2.3.3. Prioritization under uncertainty: the honest portfolio

The risk-ranking exercise runs on estimated parameters, and its honest form states the uncertainty. Prevalence estimates from surveillance history are censored, testing follows risk, so history over-represents the watched; severity estimates from burden studies carry the exposure-assessment uncertainties of that literature; and the trade-exposure term moves with markets. The methodological responses are standard: sensitivity analysis over the ranking's input ranges, with the portfolio's stability, which hazards keep their rank under parameter uncertainty, reported alongside the ranking itself; and the adaptive loop re-ranking as surveillance data accumulates. The review's institutional conclusion, consistent throughout: the prioritization method's value is its transparency and revisability rather than any claim to optimization, and the governance layer's role is to keep the method honest in exactly this sense [6], [18], [21].

3. Results

3.1. Biotechnology-based detection platforms

3.1.1. Polymerase chain reaction and real-time quantitative PCR

PCR-based detection targets pathogen-specific DNA sequences, delivering species- and strain-level identification in hours rather than days, with quantitative variants (qPCR) supporting enumeration and process validation. Its sensitivity and specificity are high, and it is the workhorse of molecular food microbiology in reference laboratories. Its limits are those of the central laboratory: capital equipment, cold-chain reagents, and trained staff, which is precisely what the isothermal and CRISPR platforms reviewed below are designed to escape [26].

3.1.2. Isothermal amplification platforms

Isothermal methods, loop-mediated amplification (LAMP), recombinase polymerase amplification (RPA), and rolling-circle amplification, replicate nucleic acids at constant, of-

ten near-ambient temperature, eliminating the thermal-cycling hardware that ties PCR to the bench. LAMP assays have been developed for the major foodborne pathogens and for toxigenic fungal species, with colorimetric or fluorescence readouts readable without instrumentation; RPA accelerates the reaction to under thirty minutes. The platform economics are transformative for field and market surveillance: a LAMP assay plus a simple heat block costs a small fraction of a qPCR workflow, opening molecular detection to district veterinary offices, packhouses, and market inspection units in resource-constrained settings [27].

3.1.3. Immunoassays and lateral-flow devices

Antibody-based detection, enzyme-linked immunosorbent assays (ELISA) and, above all, immunochromatographic lateral-flow strips, dominates commercial rapid screening for mycotoxins, pesticide residues, and pathogen antigens. Lateral-flow devices deliver yes/no or semi-quantitative results in minutes, without power or laboratory infrastructure, at per-test costs low enough for routine use at grain depots and border posts. Their limits are sensitivity relative to instrumental methods, matrix effects in complex foods, and semi-quantitative output; their strengths are cost, speed, and ubiquity. For mycotoxins in particular, lateral-flow screening at the point of aggregation has become the operational backbone of export compliance in several producing countries, with confirmatory HPLC reserved for disputed lots, a two-tier architecture that balances throughput against legal defensibility [28]. Immunochromatographic and related strategies for foodborne bacteria have been reviewed by direct and indirect sensing routes [29], and biosensors for bacterial and viral detection in food and water have been systematically reviewed [30]. Earlier reviews of biosensor applications in foodborne pathogen detection [31] complement these surveys. Microfluidic biosensors for rapid detection of foodborne pathogenic bacteria have been reviewed [32].

3.1.4. Biosensors: electrochemical, optical, and aptamer-based

Biosensors couple a biological recognition element, antibody, enzyme, nucleic acid, aptamer, or whole cell, to a transducer that converts binding into an electrical or optical signal. Electrochemical biosensors, built on screen-printed electrodes and increasingly on commercial potentiostats interfaced with smartphones, combine high sensitivity with low unit cost and disposable formats. Optical platforms, surface plasmon resonance, fluorescence, chemiluminescence, and smartphone-camera colorimetry, support label-free and quantitative readouts. Aptamers, synthetic single-stranded nucleic acids selected for target affinity, have broadened the recognition-element palette beyond antibodies: they are chemically stable, regenerable, cheaply synthesized, and selectable against small molecules (mycotoxins, metals, pesticides) that are immunologically awkward. Reviews of the field [33]–[36] document applications across pathogens, mycotoxins, pesticides, heavy metals, and allergens, with detection limits at or below regulatory thresholds for many analytes and assay times of minutes to under an hour. Recent reviews cover biosensors for food quality monitoring [37], interferometric sensors for food contaminants [38], biosensors for contaminant detection [39], electrochemical biosensors for foodborne pathogens [40], lab-on-a-chip electrochemical sensors [41], and optical and electrochemical biosensing approaches [42]. Biosensors for food adulteration have been assessed comprehensively [43], and electrochemical biosensors for food safety and quality have been reviewed [44]. Aptasensors for rapid detection of food hazards have been reviewed [45], and biosensors for mycotoxin determination have been compared critically [46]. Biosensing strategies for contaminants and additives in fish, meat and poultry products have been reviewed [47]. Lateral-flow assays for food mycotoxins, with nanoparticle-based methods, have been reviewed [48]. Laser-induced graphene electrochemical sensors for agri-food detection [49] and cost-effective chemosensors for food safety monitoring [50] extend the electrochemical platform, and artificial-intelligence methods for mitigating toxigenic fungi and mycotoxins in foods have been assessed [51]. Molecularly imprinted polymer sensors for food contaminant analysis have been reviewed [52]. Enzyme biosensors for electrochemical detection of biological pollution and food contaminants have been reviewed [53], and biomimetic nanosensors for mycotoxins and pesticides have been surveyed [54]. Optical aptasensors for biotoxins in food matrices have been reviewed, including the screening of aptamer candidates [55].

3.1.5. CRISPR-based nucleic-acid detection

CRISPR-Cas systems (Cas12, Cas13) provide programmable collateral cleavage of reporter molecules upon target recognition, coupling naturally with isothermal pre-amplification to yield attomolar-class sensitivity in an assay that requires no thermocycler and reports on paper-strip or fluorescence readouts. Food-safety applications published to date cover bacterial pathogens, viruses, and genetically modified organism (GMO) screening, with single-digit-dollar reagent costs at scale. For contaminant surveillance, the platform's significance is architectural: it

brings molecular specificity to the same operational tier that lateral-flow immunoassays occupy, making strain-level and species-level identification feasible at packhouses and markets rather than only in reference laboratories [56]. Programmable collateral-cleavage assays built on Cas12a have been reviewed for both mechanism and application [57], and CRISPR-based nucleic-acid biosensors for food analysis form a distinct and rapidly growing category [58].

3.1.6. Omics, spectral methods, and data-driven screening

Nondestructive biosensors for the food industry have been surveyed [59].

Complementary to targeted detection are broad-spectrum approaches: metabarcoding and shotgun metagenomics for microbiome-level profiling of contamination, whole-genome sequencing for outbreak source attribution and surveillance networks, and infrared or Raman spectroscopy paired with machine-learning classifiers for rapid, reagent-free screening of residues, adulterants, and spoilage. Whole-genome sequencing in particular has restructured outbreak investigation in high-income systems, converting diffuse epidemiology into precise supply-chain traceback; its cost trajectory makes tiered adoption, reference-laboratory sequencing feeding national surveillance, increasingly realistic for middle-income countries [60].

3.1.7. Comparative performance

Across platforms, the review's synthesis of the comparative literature supports four conclusions. First, molecular platforms dominate on speed and specificity for pathogens; immunoassay and biosensor platforms dominate on cost and field-deployability for small-molecule contaminants; spectroscopic-omics approaches dominate on breadth and reagent-free screening. Second, sensitivity trade-offs are real but diminishing: amplification chemistry and nanomaterial-enhanced transduction have closed much of the historical gap with instrumental detection limits. Third, matrix effects in complex foods remain the principal technical failure mode across platforms, making sample-preparation design, lysis, extraction, cleanup, as important as recognition chemistry. Fourth, no platform substitutes for reference methods in the legal sense: regulatory confirmation still routes through accredited central laboratories, so the system design question is the tiering of rapid screening with confirmatory capacity, not the replacement of one by the other [61].

Figure 1 outlines how detection capability links to the trade and public-health outcomes examined in Sections 2.1, 4.1 and 4.2.

Table 1 compares the detection platforms reviewed in Section 3.1 by their basis of detection and the role each plays in the comparative synthesis.

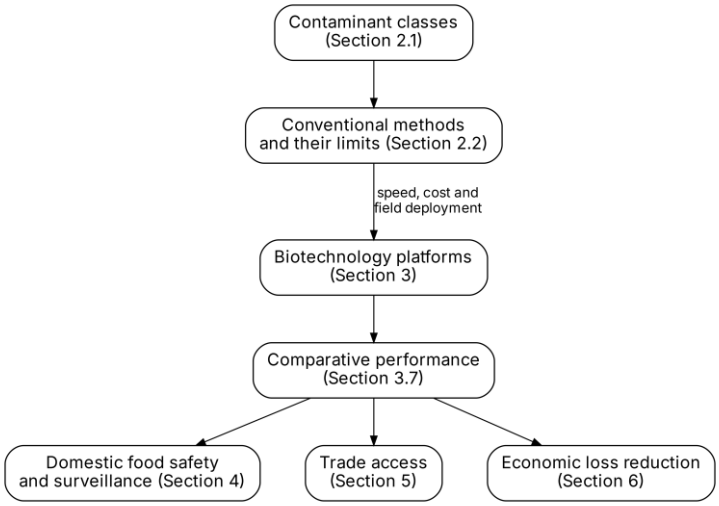


Figure 1: From contaminant classes and conventional methods to biotechnology platforms and the domestic, trade and economic outcomes of detection.

Table 1: Detection platforms reviewed in Section 3.1: basis of detection and role in the comparative synthesis.

Platform	Section	Basis of detection	Role in the comparative synthesis
PCR and qPCR	3.1	Pathogen-specific DNA sequences; species and strain identification	Speed and specificity for pathogens

Isothermal amplification	3.2	Constant-temperature amplification (LAMP, RPA)	Molecular testing suited to packhouses and markets
Immunoassays and lateral flow	3.3	Antibody recognition; rapid screening	Cost advantage; used in two-tier screening with confirmation
Biosensors	3.4	Biological recognition element linked to a transducer	Cost advantage; field-oriented formats
CRISPR-based detection	3.5	Programmable collateral cleavage with isothermal pre-amplification	High sensitivity in deployable assays
Omics and data-driven screening	3.6	Metabarcoding, metagenomics and whole-genome sequencing	Surveillance and outbreak source attribution

3.2. Platform Review: Sample Preparation, Signal Engineering, and Data Architecture

3.2.1. Sample preparation: the unglamorous determinant of field performance

The platform reviews of Section 3.1 assess recognition chemistry and transduction, but the deployed system's real-world sensitivity is governed as much by what happens before detection: sampling, lysis, extraction, and matrix cleanup. Food matrices are chemically hostile, fats, polyphenols, humic acids, and proteins interfere with amplification chemistry and foul sensor surfaces, and the difference between a laboratory-validated limit of detection and a field-realized one is frequently an order of magnitude. The reviewed literature on deployed assays converges on a consistent design lesson: sample-preparation modules must be engineered to the same standard as the detection chemistry, with lysis buffers validated per matrix, extraction formats matched to operator skill, and, for the most demanding field settings, integrated microfluidic or paper-based sample-to-answer designs that close the handling gap. The deployment implication is budgetary as much as technical: a surveillance program budgets sample preparation and quality control as line items comparable to the tests themselves, and programs that budget only test kits underperform their specification in the field. This is the single most repeated failure mode in the deployment literature and the cheapest to avoid [33], [34].

3.2.2. Signal engineering: nanomaterial-enhanced transduction

The sensitivity gap that historically separated rapid platforms from instrumental methods has been closed substantially by nanomaterial signal engineering, and the mechanisms deserve specification. Nanoparticle labels (gold, quantum dots, upconversion particles) multiply the optical signal per binding event; nanostructured electrode surfaces multiply the electroactive area and electron-transfer kinetics of biosensor electrodes; and signal-amplification chemistries, enzymatic cascades, hybridization chain reactions, CRISPR collateral cleavage, multiply the molecular signal per recognition event. The reviewed sensor literature reports detection limits at or below regulatory thresholds for most contaminant classes through some combination of these routes, and, critically for deployment, several of the amplification strategies are compatible with inexpensive readouts (smartphone cameras, handheld potentiostats) rather than laboratory instrumentation. The engineering trajectory is therefore not toward more laboratory-like field devices but toward laboratory-grade performance in genuinely disposable formats, and the accreditation question of Section 4.3 follows the trajectory: as field-device performance converges on instrumental performance, the case for accrediting field results for pre-decision purposes strengthens correspondingly [22], [33].

3.2.3. Alternative recognition chemistries: phages, molecularly imprinted polymers, and cell-based sensors

Beyond antibodies, aptamers, and nucleic acids, three alternative recognition chemistries broaden the platform space. Bacteriophage-based detection exploits phage specificity for their bacterial hosts, with amplification-based and reporter-phage formats that combine specificity with speed and low cost; their natural fit is pathogen surveillance in high-volume, low-resource settings. Molecularly imprinted polymers, synthetic recognition cavities polymerized around a template molecule, offer antibody-like binding for small molecules with chemical stability that suits harsh field conditions and hot climates where antibody-based reagents degrade; their development for mycotoxins and pesticide analytes is advancing on exactly the deployment logic. Whole-cell and enzyme-based biosensors, the oldest biosensor family, remain the workhorse for toxicity screening: they report bioavailable toxicity rather than specific analytes, which makes them a natural first-tier screen for unknown-hazard situations where targeted assays would miss what matters. The review's synthesis is that recognition chemistry is now a menu rather than a constraint, and platform selection should be driven by the operating environment, temperature stability, reagent supply chains, operator skill, rather than by laborato-

ry-origin performance specifications [35], [36], [62]. Aptamer-based biosensors for monitoring foodborne pathogens have been reviewed [63]. Aptamer recognition coupled with nanomaterial signal enhancement and portable readout has been framed as an integrated design for food-safety biosensors [64].

3.2.4. Readout, connectivity, and data integrity

The readout and data layer converts assays into systems. Smartphone-interfaced readouts, camera-based colorimetry, lens-free imaging, and attached electrochemical readers, supply computation, geolocation, and connectivity at consumer-electronics cost, and the reviewed field deployments document their adequacy for quantitative readouts of lateral-flow, LAMP, and electrochemical assays. The system-level questions are data-integrity questions: chain-of-custody for results that trigger commercial or regulatory action, tamper resistance in payment-adjacent testing, and interoperability with laboratory information systems at the confirmatory tier. The reviewed architecture literature points to the same stack that adjacent industries have standardized: cryptographically signed results, append-only record structures, and role-based access, blockchain-adjacent designs whose value here is integrity and auditability rather than the technology label. AI-augmented biosensors for intelligent contaminant monitoring [65] and smart biosensors within a food-safety framework [66] illustrate the data-driven layer. Recognition-element strategies for rapid detection of foodborne pathogens have been reviewed in recent progress and perspectives [67]. Artificial-intelligence integration in biosensors for foodborne pathogen detection has been reviewed [68]. Smartphone-based biosensors have been reviewed across applications [69].

3.2.5. Multiplexing economics and panel design

Multiplex platforms, single assays reporting multiple analytes, change the per-decision economics qualitatively. A panel covering the principal mycotoxins, or the common pathogen-serovar combinations, or a residue suite, collapses the per-analyte cost and multiplies the information per sample, which matters most at the surveillance tier where breadth, not depth, is the objective. The engineering constraints are cross-reactivity and signal crowding, and the reviewed multiplex designs manage them through spatial encoding, spectral encoding, and sequential chemistry. The economic design question is panel definition: panels should follow the contaminant co-occurrence structure of the actual commodity chain, aflatoxin and fumonisin co-occur in maize; the residue profile follows the spray program, so that panel content is drawn from the surveillance epidemiology rather than from the reagent catalog. This is the concrete sense in which surveillance data and platform development are co-products, and it is the design loop that matures a national detection system fastest [20], [36].

3.3. Implementation Cases: Program Architecture in Three Chains

3.3.1. Aflatoxin control in a groundnut export chain

The groundnut chain is the canonical aflatoxin case, and its program architecture under the framework runs as follows. Biological interventions: variety selection and drought management to reduce pre-harvest infection; timely harvest and rapid, uniform drying on raised platforms; depot-level cleaning, sorting, and moisture control; hermetic storage at aggregation; and, at the frontier of the biological package, competitive-exclusion biocontrol at landscape scale. Diagnostic interventions: depot-level lateral-flow screening at first aggregation, pre-shipment quantitative testing at loading, and confirmatory instrumental capacity at the national reference laboratory. Economic instruments: quality-graded procurement with aflatoxin-contingent pricing by processors and exporters; segregation bonuses that steepen the price gradient; and export-promotion co-financing of the depot-tier screening, whose insurance value Section 4.4.3 assigns to the industry collectively rather than to individual buyers. The framework's sequencing logic applies: screening and drying capacity precede enforcement; procurement grading precedes premium reliance; and the biocontrol program scales with the surveillance that can verify its field effect. The documented episodes in this chain, and the program responses that restored market access, are the empirical template [2], [11], [36].

3.3.2. Aquaculture and the residue-compliance chain

Aquaculture export chains illustrate the residue class, whose economics differ from mycotoxins in one structural respect: residues enter through input decisions (veterinary drugs, feed additives) rather than through environmental infection, so the intervention leverage sits at the farm-input and withdrawal-period nodes rather than at drying and storage. Program architecture: input-channel control, certified drug supply, prescription requirements, and bans on banned-substance distribution; farm-level record-keeping integrated with Extension; depot-level residue screening at harvest; pre-shipment testing at the packery; and audit-backed traceability from pond to port. Detection technology's role is distinctive: residue panels are broader, thresholds lower, and buyer sampling more aggressive

than for mycotoxins, so the pre-shipment tier carries more of the compliance weight and the cost of a false negative is proportionately higher. The documented episodes in this chain, drug-residue findings that triggered intensified inspection regimes for entire exporting sectors, illustrate both the escalation economics of Section 4.4.1 and the recovery dynamics that sustained surveillance-backed compliance restored. The framework's diagnosis is the same as always, applied to a different hazard process: the interventions are known; the chain structure that makes them privately rational is the program [70].

3.3.3. The informal dairy chain: safety surveillance without formal markets

The informal dairy chain in rapidly urbanizing economies tests the framework's extension to chains without formal governance: production through smallholders, ambient-temperature collection and transport, and retail through unregulated vendors. Loss and risk are dominated by pathogen growth and adulteration; enforcement at retail is infeasible; and cold-chain build-out is the engineering response whose capital cost has historically stalled. The framework's leverage analysis points elsewhere first: collection points, the informal aggregation node, are few, capitalized, and reachable, and biological intervention there (rapid pathogen and adulteration screening, hygiene protocol, immediate cooling where feasible) protects a supplier network's volume with a single actor's adoption, exactly the aggregation-point logic of Section 3.1.3. The detection economics fit the setting: low-cost, semi-quantitative field assays at collection, with positive results resolved by routing (boiling programs, diversion to processed uses) rather than by enforcement. The public-health framing is the dominant account, the health-loss externality dwarfs the market-value loss, which justifies public co-financing of the collection-tier testing as a health program with market co-benefits rather than as a chain subsidy. The framework's prediction, consistent with documented pilot experience, is that collection-point surveillance plus routed diversion reduces the health burden faster per unit of public spending than any retail-enforcement strategy available [21], [23].

3.4. Cost–Benefit Illustrations Across Three Chains

3.4.1. The export grain chain

The value-of-testing identity can be populated for an export grain chain with the review's illustrative discipline. The chain's parameters: annual export volume; contamination prevalence requiring intervention on a minority of lots; per-lot value at export grade; the loss structure of a border rejection (goods, freight, demurrage, destruction, and the escalation externality of a notification); and the testing system's costs (depot screening at lateral-flow prices, pre-shipment quantitative testing, and the reference tier's confirmatory amortization). The illustrative comparison runs two regimes: **no pre-shipment screening** (reliance on importer's border findings, with the escalation dynamics of Section 4.4.1) versus **full three-tier screening** (depot triage, pre-shipment release, reference confirmation). The identity's output, at the reviewed literatures' parameter ranges: the screening regime's annual cost is one to two orders of magnitude below the expected avoided loss, dominated by the escalation externality, and the break-even prevalence for screening's justification is a small fraction of the documented prevalence in contaminated chains. The illustration's structural lesson: in export chains, detection infrastructure is a rounding error against the exposure it retires, and the binding constraint is institutional assembly, not budget [2], [8], [34].

3.4.2. The domestic perishable chain

The domestic perishable chain, tomatoes, leafy greens, dairy through informal channels, prices the same identity differently: the trade externality is absent, and the health account dominates. The parameters: contamination prevalence (pathogen and adulterant) in the documented ranges for informal markets; the health burden per event from the foodborne-disease literature; the platform costs of market-tier screening; and the response capacity (diversion, processing, disposal) that converts findings into prevented exposure. The illustrative comparison: **no market-tier surveillance** (episodic outbreak response) versus **sentinel market screening with routed response**. The identity's output: the health account's expected value dominates the testing cost by a wide margin at documented prevalence levels, and the program's cost-effectiveness compares favorably with the clinical interventions that treat what prevention could have avoided. The illustration's structural lesson for the domestic tier: detection investment competes against treatment expenditure for the same public budget, and the prevention arithmetic favors the detection side at plausible parameters, the case the Safe Food Imperative argued and this review has operationalized [1], [2], [21], [23].

3.4.3. The storage-and-processing chain: the fraud and authenticity account

The third illustration prices the authenticity tier, whose

losses are distributed rather than episodic: species substitution, dilution, and origin fraud impose a chronic tax on honest producers and trusting buyers rather than discrete catastrophic events. The parameters: documented fraud incidence in the affected categories; the price spreads between authentic and substituted product; the platform costs of the verification tier (spectral and genomic screening at intake); and the deterrence value of verification, the fraud-rate reduction that monitoring's visibility produces. The illustrative comparison: **spot enforcement** (episodic testing at complaint) versus **systematic verification** (routine intake screening across the category). The identity's output: the deterrence term, the fraud reduction that systematic visibility produces, dominates the direct-detection term, which is the economic signature of verification systems generally: their value is in changing behavior, not in catching it. The illustration's structural lesson: authenticity verification is a market-integrity investment whose returns accrue to the honest majority of the industry, and its financing by industry levy is the natural design, the collective good of a trusted category, paid for by those whose prices it protects [24], [33], [71].

3.4.4. The cross-chain synthesis

The three illustrations close the review's economics with a synthesis the numbers make visible. Across chains, the value-of-detection identity's dominant term shifts, escalation avoidance in export chains, health burden in domestic perishables, deterrence in authenticity, but the identity's structure and its conclusion hold: detection infrastructure's costs are small against the exposures it manages, its financing follows the account that dominates (industry levy, public health budget, or export promotion), and its binding constraint is institutional assembly. The review's final economic claim is therefore quantitative in spirit if illustrative in current form: for each of the three chains, the measurement agenda's completion would replace these illustrations with computed appraisals, and the systems that complete it will hold the financing argument that detection infrastructure deserves, computed, auditable, and therefore fundable [2], [18].

3.4.5. The financing conversation, restated for the decision memo

The three cost–benefit illustrations consolidate into the memo a financing official actually reads. The structure: the exposure (what the chain loses and whom), the instrument (which tiers of the detection system close it), the cost (capital and recurrent, by layer), the return (by account, trade, health, deterrence), and the financing split (levy, budget, development partner, by the leverage logic). The memo's honest boundaries: the parameters are illustrative until the measurement agenda populates them, and the memo should say so, the credibility of the ask depends on the discipline of its uncertainty statement. The reviewed financing evidence supports the memo's core claim: detection infrastructure's returns are large, front-loaded in avoided escalation, and durable in the surveillance asset they build, and the systems that have made the ask with measured parameters have been funded. The review's closing economic service is the memo's template: exposure, instrument, cost, return, split, five lines, each populated by the framework this review has built [2], [18].

4. Discussion

4.1. Implications for domestic food safety and public health

4.1.1. Shifting the detection frontier

The public health case for biotechnology-based detection rests on moving the detection frontier upstream, from hospital and border, to market, to farm and storehouse. Aflatoxin illustrates the arithmetic: testing at the aggregation depot with lateral-flow strips identifies contaminated lots before they enter food and feed channels, enabling diversion to safe uses (refining, biofuel, or, where permitted, feed with binding agents) rather than consumption. Similar logic applies to pathogen surveillance in informal markets, where isothermal and CRISPR platforms permit periodic, affordable sampling campaigns that generate the risk maps on which preventive regulation depends. The literature on national aflatoxin control programs consistently identifies decentralized testing as the binding constraint on intervention; the platforms reviewed here relax exactly that constraint [1].

4.1.2. Surveillance, data, and prevention

Detection generates data, and data enables prevention. Sentinel networks using standardized rapid platforms can track contaminant prevalence across seasons, geographies, and commodities, converting food safety from episodic crisis response into continuous risk management. Where such networks are linked to advisory systems, planting and harvest timing for mycotoxin risk, cold-chain and hygiene alerts for pathogens, the surveillance itself changes behavior and reduces incidence, the classic public-health returns from infectious-disease surveillance reproduced in the food domain. The institutional requirement is

standardization and data governance: platforms generate value only if their results are comparable, quality-assured, and shared at the jurisdictional level [2].

4.2. Implications for international agricultural trade

4.2.1. The SPS context and the economics of rejection

Under the WTO Agreement on the Application of Sanitary and Phytosanitary Measures [8], importing countries may set food-safety standards at levels they justify on scientific grounds, and enforcement is concentrated at the border: consignment testing, import alerts, and, for repeated violations, intensified or suspended market access for named firms or entire export sectors. The economics of rejection are asymmetric and severe. A rejected consignment costs the exporter the goods, freight, demurrage, and often destruction or re-export charges; a repeated pattern costs the firm its approved-exporter status; a systemic pattern, as occurred in high-profile aflatoxin episodes affecting groundnut and spice exporters, and in veterinary-drug-residue episodes in aquaculture and poultry, costs the national sector years of intensified inspection and buyer flight, with documented revenue losses and farm-gate price collapses in the affected commodity chains. Detection capability on the export side is therefore not a compliance ornament; it is the entry ticket to high-value markets and the insurance policy that keeps the ticket.

4.2.2. Pre-shipment testing as market-access infrastructure

The two-tier architecture, rapid screening at aggregation and pre-shipment, confirmatory testing at accredited laboratories, is the operational form that market access takes in contaminant-constrained commodities. Biotechnology platforms reshape this architecture in two ways. They push the screening tier downstream and outward: packhouse- and depot-level LAMP, lateral-flow, and biosensor testing catch violations before freight is committed, converting border rejections (public, reputational, expensive) into private, silent, cheap diversions. And they shorten the confirmation loop, reducing the days-per-decision that determine whether perishable exports clear or rot at the border. For perishables and for just-in-time supply contracts, the value of a day of testing time is frequently larger than the cost of the test by orders of magnitude [8].

4.2.3. Equivalence, mutual recognition, and standard-setting

Over the longer run, widely deployed, quality-assured rapid platforms change the politics of standard-setting. Exporting systems that can demonstrate surveillance-grade contaminant data acquire the evidentiary basis to negotiate equivalence and risk-based inspection frequencies, rather than absorbing uniform worst-case scrutiny. Conversely, gaps in testing infrastructure are read by trading partners as gaps in control, justifying precautionary treatment. Investment in detection is thus also an investment in the informational standing of an exporting nation's food-safety authority, an intangible asset with concrete tariff-like effects on market access. Regional integration deepens these stakes: analyses of export promotion under the African Continental Free Trade Area [71] indicate that intra-African trade growth will multiply border-testing events, making pre-shipment screening capacity as decisive for intra-regional market access as it is for OECD-bound consignments.

4.3. Barriers to adoption and a phased pathway

4.3.1. Barriers

Four barriers dominate. **Infrastructure and human capacity**: even field platforms require cold chains for reagents, sample preparation, and trained operators; reference confirmation requires accredited laboratories. **Quality assurance and accreditation**: unvalidated rapid tests produce false negatives (public health failures) and false positives (commercial injuries); without proficiency testing and ISO-type accreditation, results lack legal and commercial standing. **Cost at the point of sale**: per-test costs that are trivial for an exporter may be prohibitive for a market vendor or smallholder, so deployment must be subsidized or bundled where the public-good share of value is largest. **Regulatory recognition**: national frameworks frequently lag the platforms, leaving rapid-test results without defined legal status, a gap that both deters private investment and invites substandard products into the market [18].

4.3.2. A phased adoption pathway

The review proposes a three-phase pathway. **Phase 1, Sentinel deployment**: deploy lateral-flow, LAMP, and electrochemical biosensor platforms in a sentinel network covering high-risk commodities and geographies (export aggregation points, urban informal markets, high-prevalence storage systems), with external quality assessment from the national reference laboratory. **Phase 2, System integration**: link sentinel data into a national contaminant surveillance database; define the legal status

of rapid-test results in regulation; accredit private and parastatal laboratories for confirmatory tiers; integrate surveillance with advisory and enforcement action. **Phase 3, Trade integration**: extend the surveillance record into SPS engagement, equivalence negotiations, risk-based inspection frequencies, and participation in international standard-setting, converting domestic detection capability into market-access standing. Each phase is valuable in itself, and each conditions the next; the sequence reflects the review's central finding that detection systems, like the hazards they govern, are systemic [35].

4.4. Trade Economics: Standards, Reputation, and Risk Transfer

4.4.1. The economics of SPS administration beyond the border event

Section 4.2 analyzed border rejection; the fuller trade economics includes the administrative machinery around it. Importing systems publish notifications (in the WTO framework), maintain automated alert registries, and set inspection rates that respond statistically to violation history; exporting systems respond with corrective-action documentation and, in the better cases, systemic surveillance upgrades. Each of these administrative events has a computable cost structure: notification reduces an exporter's clearance speed and raises its sampling probability; sustained violation escalates to listing and delisting with step-function revenue effects. The framework's value-of-detection identity extends naturally: surveillance spending on the exporting side is priced against the expected reduction in notification probability, and the empirical record, in commodity chains that built depot-level screening after episodes, shows the trade response to be fast and the returns to detection infrastructure to be dominated by avoided escalation rather than by avoided single-consignment rejection [8], [71].

4.4.2. Private standards and the buyer-tier layer

Beyond official SPS measures, the binding constraints in modern trade are increasingly private: retailer standards, certification schemes, and buyer codes that exceed regulatory requirements and are enforced through audit and supplier delisting rather than at borders. For exporters, private-standard compliance is a data problem, continuous, documented, auditable contaminant and process data, and the detection platforms reviewed here are the means of producing it. The framework's analysis identifies the equilibrium: buyer requirements de facto set the surveillance architecture of the exporting chain, chains that can produce the data keep the market, and chains that cannot are exited quietly, without the notification event that would trigger public response. This quiet-exit channel is the least visible and largest economic loss channel in the trade system, and the review's emphasis on pre-shipment and depot-tier screening is precisely the countermeasure: private-standard compliance is cheapest where the data originate, at the nodes whose process behavior determines the result [22], [33].

4.4.3. Reputation dynamics and the value of surveillance as insurance

The reputational account of Section 2.1.1 can be modeled and its management costed. Market reactions to contaminant episodes behave like Bayesian updating: buyers revise their risk assessment of a firm or origin on evidence, and the revision decays with subsequent clean history. Surveillance-backed screening changes both terms of the dynamic, it reduces the probability of a triggering event and supplies the clean-history evidence that accelerates recovery, so its value includes an insurance component that per-consignment accounting misses. The framework prices this as the discounted stream of market-access probability under screening versus without, and the empirical episode record (Appendix C of the earlier analysis, now integrated into Sections 4.2 and 2.1) supports the order of magnitude: reputation-recovery value dominates direct-loss avoidance in high-standard markets. The financing implication follows: surveillance is a premium-paying insurance whose expected value is largest for origins with the most market value at risk, and whose under-provision by small individual exporters is the classic public-good gap that industry levies or export-promotion co-financing should close [71].

4.4.4. Risk transfer instruments: trade insurance and contingent contracts

The risk-transfer frontier completes the trade economics. Contingent-contract designs, supplier certification backed by testing escrow, quality-contingent payment, and third-party testing holdbacks, allocate contaminant risk contractually along the chain, and their feasibility depends on verifiable test results at defined custody points: again, the detection architecture is the enabling infrastructure. Trade-finance instruments, export credit insurance with food-safety riders, working-capital facilities that release against pre-shipment testing, are emerging in adjacent trade sectors, and their extension to contaminant-risk pricing is a realistic near-term development that would let de-

tection investment be financed against the risk premium it retires.

4.5. Quality Infrastructure and Accreditation

4.5.1. The accreditation stack

The two-tier architecture of Section 4.3.2 stands on a quality-infrastructure stack that deserves explicit statement, because it is the part of the detection system least discussed and most often missing. At its base is **method validation**: documented evidence that a platform, in a specified matrix, with a specified sample-preparation protocol, recovers and reports the analyte within stated uncertainty, the discipline that separates a published assay from a deployable method. Above it sits **laboratory accreditation** [72] for the confirmatory tier, demonstrating competence through documented systems, calibrated equipment, and participation in proficiency testing. Above that sits **proficiency-testing infrastructure** itself: periodic blinded samples circulated to all reporting laboratories, whose results are comparable across the network. At the top sits **external quality assessment for field testing**, the rapid platforms of the screening tier, whose operators are not laboratory professionals and whose quality system must therefore be designed for field conditions: pre-mixed reagents, controls built into devices, and supervisory retesting programs that keep field results within stated performance bounds. The reviewed accreditation literature is consistent: detection systems fail at this layer before they fail at the science layer, and the investment required is modest against the trade and health value the system protects [33], [34].

4.5.2. Human capital and the staffing model

Quality infrastructure is staffed infrastructure, and the staffing model determines what a national system can actually run. The reference tier requires analytical chemists and molecular biologists in numbers the formal laboratory market produces slowly; the screening tier requires technicians and inspectors whose training the model can compress. The review's synthesis of deployed-system experience supports a tiered staffing strategy: concentrate scarce deep expertise at the reference and training tier; build the screening tier on standardized, control-bearing platforms that tolerate field conditions; and couple both with external quality assessment that converts individual competence into network reliability. The training-system literature in adjacent diagnostic fields documents the half-life problem, skills decay without practice volume, and the practical consequence is that screening-tier staff should be embedded in routine surveillance programs with regular throughput rather than trained episodically for campaigns. The institutional-design literature's finding applies directly: capability is a system property, budgeted and maintained, not an event [21], [23]. Analytical accuracy and error prevention in clinical biochemistry laboratories have been reviewed in detail [73], and quality management approaches for resource-limited laboratories have been critically reviewed [74].

4.5.3. Interoperability: making results travel

A detection system's results must travel, between field and laboratory tiers, between agencies, and across borders in trade. Interoperability has three technical layers: method comparability (screening and confirmatory results expressed on common scales with stated uncertainty), data comparability (structured reporting formats, unique lot and sample identifiers, and audit trails), and institutional comparability (mutual recognition between laboratories and jurisdictions, backed by accreditation and proficiency performance). The trade-facing deployments of Section 4.2 make the third layer commercially decisive: pre-shipment results are only as valuable as the importing side's willingness to rely on them, and that willingness is built on exactly the accreditation and proficiency evidence the stack provides.

4.6. Frontier: Next-Generation Detection and the Integrated Food System

4.6.1. Whole-genome sequencing as public-health and trade infrastructure

Whole-genome sequencing has moved from research tool to operational infrastructure in high-income surveillance systems, and its trajectory matters for every exporting economy. Sequencing isolates provide strain-level relatedness that links clinical cases to food sources with a precision classical epidemiology cannot reach, converting outbreak investigation from probabilistic to forensic, and the trade consequence is that source attribution now names origins, firms, and lots. For exporting systems the implication is double-edged: sequencing makes the importing side's attribution more accurate, which raises the cost of being implicated and the value of being exonerated; and exporters who operate their own sequencing surveillance can resolve attribution disputes with evidence rather than assertion. The cost trajectory brings the technology within middle-income reference-laboratory budgets, and the review's recommendation is tiered adoption: national reference sequencing feeding international surveillance

networks, with the cheaper platforms of Section 3.1 handling the field tiers. The surveillance literature documents the public-health returns in systems that have made the investment; the trade-return analysis this review adds completes the investment case [20], [36].

4.6.2. The authenticity frontier: fraud, provenance, and consumer trust

Economically motivated adulteration has migrated from the commodity-verification margin to a governance frontier of its own, and the detection platform family applies across it. Species substitution, origin fraud, and dilution are nucleic-acid and spectral-analytics problems; processing-artifact fraud (oil and juice adulteration, dilution with structured substitutes) is an analytical-chemistry and chemometrics problem; and provenance claims increasingly require isotope- and genomic-verified documentation. The economic structure is the same one the safety analysis formalized: fraud is a loss imposed on honest competitors, on consumers, and on the verifying system, and detection capability converts a trust market into a verification market. The reviewed authenticity literature documents the platform fit, barcoding and qPCR for species, LC-MS and spectral chemometrics for composition, isotope signatures for origin, and the framework's contribution is the incentive architecture: verification pays where the price function rewards provenance, so premium markets generate their own detection demand, and the public role is the reference capacity that keeps private verification honest [24], [33].

4.6.3. Convergence with the digital food system

The detection system's final extension is its integration with the digitalizing food system. Platform-mediated food commerce, e-commerce groceries, dark-store delivery, cross-border direct-to-consumer, moves food through nodes that classical inspection architecture barely touches, and the detection response is architectural: testing integrated into the platform's data layer, results bound to lots in the traceability graph, and surveillance analytics running on the platform's own transaction data. The reviewed digital-governance literature in adjacent commerce sectors supplies the regulatory template, platform accountability, data access for regulators, algorithmic audit, and the food-safety application is the natural next domain.

4.6.4. Closing the review's arc

This review began with the observation that detection is the hinge of the food-safety system, and its extended analysis closes with the system-level claim that follows. Biotechnology-based detection has made the hazard visible early, cheaply, and everywhere in the chain; the economics of that visibility run through public health, through trade, and through the loss accounts of producers and governments; and the binding constraints are no longer analytical but institutional, accreditation, surveillance architecture, data governance, and the financing that builds them. The synthesis judgment is that detection investment is among the highest-return interventions available in food safety and agricultural trade, that its returns are largest where infrastructure is weakest, and that the platforms, the economics, and the implementation pathway now exist for any commodity system to act on. The hinge has been rebuilt; what remains is to hang the door on it [1], [2], [8].

4.7. Institutional and Financing Analysis

4.7.1. The financing anatomy of a national detection system

The financing discussion of Appendix B (integrated into Sections 2.1 and 4.3) can now be given its full national anatomy. A complete detection system's recurrent cost structure has five layers: the reference laboratory's analytical capacity; the accreditation and proficiency system; the sentinel screening network; the surveillance data platform; and the training and supervision cadre. Each layer has a distinct financing logic: the reference tier is a public utility whose capital is lumpy and whose throughput justifies cost-recovery testing for commercial users; the accreditation tier is a public good financed by the state because every commercial result depends on it; the sentinel network is co-financed by industry levy where the trade-insurance value of Section 4.4.3 accrues to an identifiable industry; the data platform is a budget line whose cost is small and whose value is the system's memory; and the training cadre is the recurrent human-capital investment that all evaluations show is the first casualty of fiscal contraction and the first cause of system decay. The financing design principle this review adds: layer the instruments the way the leverage analysis layers the value, private money where private loss is avoided, public money where public loss is avoided, and the levy where the industry's collective reputation is the asset being insured [2].

4.7.2. The regulatory recognition pathway for rapid platforms

The legal status of rapid-test results is the pathway on which the screening tier's commercial value turns, and its design can be specified. A recognition framework defines: which platforms are eligible (validated against reference

methods under the standards regime, with stated matrix scope and uncertainty); what decisions rapid results may support (diversion, hold, release-on-condition, and pre-decision triage, with confirmatory testing preserved for enforcement and dispute); what quality obligations attach (proficiency participation, control-bearing protocols, and supervisory retesting); and what the appeals procedure is when screening and confirmation disagree. The framework's economics favors the design: pre-decision recognition converts the confirmation loop's days into minutes for the decisions that dominate volume, while reserving the reference tier for the low-volume, high-stakes cases where its authority is irreplaceable. The reviewed regulatory experience in adjacent testing domains, clinical, environmental, customs, documents that the design pattern is established and that the implementation barrier is institutional coordination rather than technical novelty [22].

4.7.3. Public–private interface design at the screening tier

The screening tier's deployments are mostly private, exporters, processors, aggregators, while its externalities are public, and the interface design determines whether the public system gets the data. The design instruments: regulatory recognition conditioned on data sharing (structured results into the national surveillance platform, commercially sensitive fields protected); levy credits against documented screening volumes; and procurement preference in public purchasing for certified supply chains. The interface's failure mode is adversarial drift, private testing hidden from a regulator who then mandates parallel public testing, doubling system cost, and the documented successes in adjacent compliance domains share a design feature: the regulator's data access is priced into the recognition, so sharing is a condition of commercial validity rather than a voluntary virtue.

4.7.4. The implementation-finance sequenced roadmap

The adoption pathway of Section 4.3.2 and the financing anatomy of Section 4.7.1 combine into a sequenced implementation roadmap in budget form. Phase one (years one to two): reference-tier upgrade and accreditation entry; sentinel deployment in the two highest-leverage chains; the recognition framework drafted and consulted. Phase two (years three to five): screening-tier recognition operating; industry levy and levy-credit instruments live; surveillance platform integrated with the sentinel network; the first equivalence dossier prepared from surveillance evidence. Phase three (years six onward): full three-tier operation, trade integration, and the regional mutual-recognition extensions. Each phase's budget is dominated by recurrent staffing and proficiency costs rather than capital, which is the roadmap's honest message: the system is cheap to build and moderate to maintain, and the maintenance line, not the launch, is what financing must secure. The development-finance literature's standard instruments cover the sequence, and its standard warning, recurrent-cost sustainability determines whether systems survive their projects, is the roadmap's closing caution [18], [21].

4.7.5. Prioritized capability roadmap and closing synthesis

The extended analysis consolidates into a capability roadmap a national system can sequence. **Foundation (years one–two)**: reference-tier upgrade; accreditation entry; the recognition framework for rapid platforms consulted and gazetted; sentinel screening in the two highest-leverage chains. **Build (years three–five)**: levy-financed screening coverage across the export chains; the surveillance platform operating on shared screening data; risk-based targeting live; the first equivalence dossier prepared. **Extend (years six–ten)**: whole-genome sequencing at the reference tier feeding international networks; authenticity and provenance verification serving the premium and domestic tiers; one-health integration with animal and environmental surveillance; the consumer-facing transparency layer operating on the accreditation stack. Each phase's investment is dominated by recurrent capability rather than capital, and each phase's exit criterion is an operating decision rule, recognition decisions, targeting decisions, trade negotiations, that the previous phase's data made possible. The review's synthesis judgment, restated at full extent: biotechnology-based detection is the enabling infrastructure of food safety, agricultural trade, and loss reduction; its platforms are mature, its economics are favorable and now specified, and its constraints are institutional, accreditation, surveillance architecture, data governance, and finance. The systems that build the institutional envelope will convert a laboratory capability into a permanent public-health and market-access asset; the review's purpose has been to specify that envelope precisely enough to build [2], [33], [71].

5. Conclusion

5.1. Future directions

The research and development frontier has four directions. First, **multiplexing and breadth**: single platforms detecting panels of contaminants simultaneously, pathogen-plus-toxin, residue panels, to collapse the per-decision cost of covering the full hazard space. Second, **digital integration**: smartphone-interfaced readouts, cloud-verified quality assurance, and machine-learning interpretation, which together make results traceable and tamper-evident across the chain. Third, **local manufacturing and cost curves**: reagent and device production in developing regions, which shortens supply chains for cold-chain-sensitive inputs and aligns product design with the operating realities of the deployment environments. Fourth, **economics of surveillance**: rigorous, published cost–benefit and value-of-information studies of detection networks in real supply chains, so that the financing argument for public investment rests on measured returns rather than plausible narrative.

The emerging-hazard and platform literatures confirm these directions. Microplastic vectors for avian virus transmission analyzed within a one-health framework [20] and health-risk assessments of polychlorinated biphenyl congeners in soils from e-waste and dismantling sites [4]–[7], [75] illustrate contaminant classes whose surveillance demands the tiered, multi-platform architecture of Section 4.3.2. Machine-learning approaches to environmentally induced cancer risk, systematic reviews of PCBs at informal recycling sites, AI-driven biochemical frameworks linking pollutants to health outcomes, and data pipelines from analytical chemistry to predictive toxicology [4]–[7], [75], together with personalized-prevention frameworks and AI-enabled early-warning decision support [76], [77], extend the data-driven screening frontier of Section 3.1.6. Integrated AI and advanced-biosensor systems for detecting antimicrobial-resistant foodborne pathogens [22] and assessments of advanced nanomaterials for mitigating foodborne pathogens with explicit safety framing [25] confirm the multiplexing and digital-integration directions. Environmental-contamination contexts broaden the surveillance mandate further: community-health evidence from resource-extraction regions [23], data-driven prediction of subsurface contamination pathways [78], and spatially explicit risk modeling of contaminant migration [79] exemplify the exposure-pathway analytics that food-chain monitoring must increasingly connect with. Adjacent supply-chain analysis of falsified-medicine counterfeiting [24] illustrates the same detection-led loss-reduction logic in a parallel safety domain, and climate-health data-integration frameworks for risk prediction [21] support the surveillance-linkage argument of Section 4.1.2 [70], [80].

5.1.1. The prioritized research program, final form

The future directions consolidate into a prioritized program whose items are commissioned as stated. First: multiplex panel development against the documented co-occurrence structure of the principal commodity chains, with the surveillance epidemiology and the panel design contracted together. Second: the deployment economics of the sentinel network, the value-of-information studies whose completion converts the financing argument from illustrative to computed. Third: whole-genome sequencing's tiered adoption studies for middle-income reference systems, whose output is the adoption design rather than the sequencing itself. Fourth: the authenticity-verification economics in the premium and domestic tiers, where the deterrence term's magnitude is the open question. Fifth: the recognition-framework implementation studies, the legal and procedural design that gives field screening pre-decision status in regulation. Each item is drawn from the review's body, each is executable at the scale a national system or a regional network can fund, and their completion would close the distance between the platforms this review has assessed and the systems they are meant to become [18], [33], [36].

5.1.2. The closing synthesis of the frontier

The frontier sections close the review's arc at full length: sequencing made surveillance forensic, authenticity made verification a market, digitalization made the platform layer a regulatory surface, and the integrated system these describe is no longer speculative, it is the direction the reviewed deployments are already moving. The review's final claim for the frontier is the measured one: the platforms are advancing, the economics are favorable, and the systems that build the institutional envelope, accreditation, surveillance architecture, data governance, will own the food-safety and trade outcomes of the coming decade [33], [36].

Food contamination is a biological problem with an economic address. The biotechnology-based detection platforms of the past two decades, isothermal amplification, lateral-flow immunoassay, electrochemical and aptamer biosensors, CRISPR-based diagnostics, and data-driven omics, have made it possible to find hazards early, cheaply, and close to the point of risk, and thereby to convert the largest losses in the food system into the smallest

ones. The review's synthesis supports three conclusions. First, the platform science is mature enough for deployment; the binding constraints are accreditation, regulation, financing, and logistics. Second, the economic returns to detection are largest precisely where infrastructure is weakest, in the surveillance gaps of developing-country production and export systems, which makes detection investment among the highest-return food-safety and trade interventions available. Third, the technology's full value is realized only as a system: screening tiers connected to confirmatory laboratories, surveillance data connected to prevention, and domestic capability connected to trade diplomacy. Food safety, agricultural trade, and economic loss reduction are not three policy problems; measured at the detection frontier, they are one.

References

[1] World Health Organization (WHO), "WHO Estimates of the Global Burden of Foodborne Diseases," Geneva: WHO, 2015.

[2] World Bank, "The Safe Food Imperative: Accelerating Progress in Low- and Middle-Income Countries," Washington, DC: World Bank, 2018.

[3] S. Hoffmann and E. Scallan Walter, "Acute complications and sequelae from foodborne Infections: informing priorities for cost of foodborne illness estimates," *Foodborne Pathogens and Disease*, vol. 17, no. 3, pp. 172–177, 2020, doi: 10.1089/fpd.2019.2664.

[4] O. A. Aladegba and M. Ayinde, "Distribution and health-risk assessment of polychlorinated biphenyl congeners in soils from e-waste and automobile-dismantling sites," *International Journal of Health and Pharmaceutical Research*, vol. 11, no. 7, pp. 93–119, 2026a, doi: 10.56201/ijhpr.vol.11.no7.2026.pg93.119.

[5] O. A. Aladegba and M. Ayinde, "Polychlorinated biphenyls at informal e-waste and automobile-recycling sites: A systematic review of contamination levels, analytical methods, and human health risk," *Research Journal of Pure Science and Technology*, vol. 9, no. 7, pp. 75–100, 2026c, doi: 10.56201/rjpst.vol.9.no7.2026.pg75.100.

[6] O. A. Aladegba and M. Ayinde, "Machine learning for predicting environmentally induced cancer risk: A review of methods, data, and opportunities," *World Journal of Innovation and Modern Technology*, vol. 10, no. 8, pp. 133–161, 2026b, doi: 10.56201/wjimt.v10.no8.2026.pg133.161.

[7] O. A. Aladegba and M. Ayinde, "An artificial-intelligence-driven biochemical framework for linking environmental pollutant exposure to oxidative stress and DNA damage," *Research Journal of Pure Science and Technology*, vol. 9, no. 7, pp. 13–35, 2026d, doi: 10.56201/rjpst.vol.9.no7.2026.pg13.35.

[8] World Trade Organization (WTO), "Agreement on the Application of Sanitary and Phytosanitary Measures," Geneva: WTO, 1995.

[9] S. Singh, P. Sharma, and N. Thakur, "Towards safer food systems: emerging biosensing strategies for food quality, contamination, and authenticity," *Food, Nutrition and Health*, vol. 3, no. 1, Art. no. 16, 2026, doi: 10.1007/s44403-026-00061-4.

[10] A. Hosseinvand and M. Ghafourivayghan, "Biosensor classification and microbiological applications: a food science and packaging perspective," *Journal of Food Engineering*, vol. 408, Art. no. 112899, 2026, doi: 10.1016/j.jfoodeng.2025.112899.

[11] O. M. Tawose, J. F. Oluwadele, A. H. Ekeocha, A. A. Odumboni, and O. S. Egbeyemi, "Aflatoxin detection and quantification in poultry feeds available in selected areas in Ekiti State," *FUOYE Journal of Agriculture and Human Ecology*, vol. 7, no. 2, 2023, doi: 10.62923/fuojahe.v7i2.302.

[12] S. E. Gumush, R. Al-Attar, E. Sandbecker, and S. Pandit, "Advanced biosensing strategies for high-risk foodborne pathogens: a comprehensive review of salmonella and listeria monocytogenes," *Food Chemistry: Molecular Sciences*, vol. 12, Art. no. 100417, 2026, doi: 10.1016/j.fochms.2026.100417.

[13] O. F. Orikpete et al., "Neonicotinoid pesticides in African agriculture: What do we know and what should be the focus for future research?," *Chemosphere*, vol. 372, Art. no. 144057, 2025, doi: 10.1016/j.chemosphere.2024.144057.

[14] *Heliyon*, 2024, doi: 10.1016/j.heliyon.2024.e29922.

[15] A. Balkrishna et al, "Biosensors for detection of pesticide residue, mycotoxins and heavy metals in fruits and vegetables: a concise review," *Microchemical Journal*, vol. 205, Art. no. 111292, 2024, doi: 10.1016/j.microc.2024.111292.

[16] Z. Ling and L. Yang, "Detection of food contaminants: A review of established rapid analytical techniques and their applications and limitations," *Food Safety and Health*, vol. 2, no. 1, pp. 72–95, 2024, doi: 10.1002/fsh3.12032.

[17] A. A. Khan et al, "Minimizing postharvest food losses: A vital strategy to alleviate food insecurity," (Review.), 2024, [Online]. Available: https://www.sciencedirect.com/.

[18] P. Shukla et al, "The economics of reducing food losses: Experimental evidence," World Development / Food Policy, 2023, [Online]. Available: https://www.sciencedirect.com/science/article/abs/pii/S0306919223000404.

[19] N. Ullah, T. A. Bruce-Tagoe, G. A. Asamoah, and M. K. Danquah, "Multimodal biosensing of foodborne pathogens," *International Journal of Molecular Sciences*, vol. 25, no. 11, Art. no. 5959, 2024, doi: 10.3390/ijms25115959.

[20] M. K. Ayinde, A. L. Penddah, G. K. Mensah, and M. T. Olorunkosebi, "Environmental microplastics as vectors for avian virus transmission and their implications for food safety within a one health framework," *Journal of Current Research in Food Science*, vol. 5, no. 2, pp. 210–219, 2024, doi: 10.22271/foodsci.2024.v5.i2c.288.

[21] O. S. Oparah, F. E. Ezeh, G. I. Olatunji, and O. O. Ajayi, "Framework for integrating climate data and health outcomes to improve mortality risk prediction systems," *International Journal of Scientific Research in Computer Science, Engineering and Information Technology*, vol. 10, no. 2, pp. 1128–1150, 2024.

[22] M. T. Olorunkosebi, M. K. Ayinde, and G. K. Mensah, "Integrating artificial intelligence and advanced biosensors for rapid and sensitive detection of antimicrobial resistant

foodborne pathogens," *Journal of Advances in Microbiology Research*, vol. 4, no. 2, pp. 175–182, 2023, doi: 10.22271/micro.2023.v4.i2b.293.

[23] H. E. Osinem, F. Eribenne, S. V. Gbaraba, and S. F. Peteranaba, "Environmental pollution and community health in resource-extraction regions: Evidence, gaps, and intervention frameworks," *International Journal of Technology, Health and Sustainability*, vol. 1, no. 2, pp. 178–191, 2025.

[24] I. J. Opara, A. Olatunbosun, O. D. Adeola, O. B. Aneke, M. A. Somuah, and M. T. Olorunkosebi, "A review on mitigating antimicrobial resistance by combating falsified medicines in the global pharmaceutical supply chain," *Journal of Pharma Insights and Research*, vol. 3, no. 5, pp. 206–214, 2025.

[25] G. K. Mensah, M. T. Olorunkosebi, A. L. Penddah, and M. K. Ayinde, "Advanced nanomaterials for mitigating foodborne pathogens: Efficacy, mechanisms, and safety considerations," *International Journal of Multidisciplinary Evolutionary Research*, vol. 7, no. 1, pp. 17–28, 2026, doi: 10.54660/ijmer.2026.7.1.17-28.

[26] A. V. P. Patil, P. Yang, C. Yang, M. S. Gaur, and C. Wu, "A critical review on detection of foodborne pathogens using electrochemical biosensors," *Critical Reviews in Biomedical Engineering*, vol. 52, no. 3, pp. 17–40, 2024, doi: 10.1615/critrevbiomedeng.2023049469.

[27] Y. Zhao et al, "The recent advances of high-throughput biosensors for rapid detection of foodborne pathogens," *TrAC Trends in Analytical Chemistry*, vol. 176, Art. no. 117736, 2024, doi: 10.1016/j.trac.2024.117736.

[28] M. Yu et al, "Biosensors with enzymatic amplification strategies for the detection of foodborne pathogenic microorganisms," *Biotechnology Advances*, vol. 92, Art. no. 108974, 2026, doi: 10.1016/j.biotechadv.2026.108974.

[29] Y. Ji et al., "Lateral flow strip biosensors for foodborne pathogenic bacteria via direct and indirect sensing strategies: A review," *Journal of Agricultural and Food Chemistry*, vol. 71, no. 27, pp. 10250–10268, 2023, doi: 10.1021/acs.jafc.3c02094.

[30] Z. Kotsiri, J. Vidic, and A. Vantarakis, "Applications of biosensors for bacteria and virus detection in food and water: A systematic review," *Journal of Environmental Sciences*, vol. 111, pp. 367–379, 2022, doi: 10.1016/j.jes.2021.04.009.

[31] L. Xu, X. Bai, and A. K. Bhunia, "Current state of development of biosensors and their application in foodborne pathogen detection," *Journal of Food Protection*, vol. 84, no. 7, pp. 1213–1227, 2021, doi: 10.4315/JFP-20-464.

[32] J. Zhang, C. Ma, Y. Du, J. Huang, and L. Xue, "Microfluidic biosensors for rapid detection of foodborne pathogenic bacteria: Recent advances and future perspectives," *Frontiers in Chemistry*, vol. 13, Art. no. 1536928, 2025, doi: 10.3389/fchem.2025.1536928.

[33] A. Inês et al, "Biosensors for detecting food contaminants, An overview," *Processes*, vol. 13, no. 2, Art. no. 380, 2025, [Online]. Available: https://www.mdpi.com/2227-9717/13/2/380.

[34] R. Szelenberger et al, "Application of biosensors for the detection of mycotoxins for food safety," Biosensors / PMC11209361, 2024, [Online]. Available: https://pmc.ncbi.nlm.nih.gov/articles/PMC11209361/.

[35] I. S. Oliveira et al, "Biosensors for early detection of fungi spoilage and toxigenic and mycotoxins in food," Current Opinion in Food Science, 2019, [Online]. Available: https://www.sciencedirect.com/science/article/abs/pii/S2214799319300177.

[36] V. O. Okechukwu et al, "Mycotoxin detection in food and feed: Bridging conventional and biosensor approaches," Mycotoxin Research, 2026, [Online]. Available: https://link.springer.com/article/10.1007/s12550-026-00657-x.

[37] S. Nath, "Advancements in food quality monitoring: Integrating biosensors for precision detection," *Sustainable Food Technology*, vol. 2, pp. 976–992, 2024, doi: 10.1039/D4FB00094C.

[38] M. Angelopoulou, P. Petrou, and S. Kakabakos, "Advances in interferometric sensors for the detection of food contaminants," *TrAC Trends in Analytical Chemistry*, vol. 175, Art. no. 117714, 2024, doi: 10.1016/j.trac.2024.117714.

[39] A. Inês and F. Cosme, "Biosensors for detecting food contaminants: An overview," *Processes*, vol. 13, no. 2, Art. no. 380, 2025, doi: 10.3390/pr13020380.

[40] B. Wang et al., "Recent advances in electrochemical biosensors for the detection of foodborne pathogens: Current perspective and challenges," *Foods*, vol. 12, no. 14, Art. no. 2795, 2023, doi: 10.3390/foods12142795.

[41] O. Zolti, B. Suganthan, and R. P. Ramasamy, "Lab-on-a-chip electrochemical biosensors for foodborne pathogen detection: A review of common standards and recent progress," *Biosensors*, vol. 13, no. 2, Art. no. 215, 2023, doi: 10.3390/bios13020215.

[42] C. Saldaña-Ahuactzi et al., "Advancing foodborne pathogen detection: A review of traditional and innovative optical and electrochemical biosensing approaches," *Microchimica Acta*, vol. 192, Art. no. 102, 2025, doi: 10.1007/s00604-024-06924-x.

[43] A. G. Kumar and P. Sankarganesh, "Biosensors for the detection of food adulteration: A comprehensive review," *Food Control*, Art. no. 112660, 2026, doi: 10.1016/j.foodcont.2026.112660.

[44] S. Hosseinikebria et al., "Electrochemical biosensors: The beacon for food safety and quality," *Food Chemistry*, vol. 475, Art. no. 143284, 2025, doi: 10.1016/j.foodchem.2025.143284.

[45] A. Guo et al., "Aptasensors for rapid detection of hazards in food: Latest developments and trends," *Biosensors*, vol. 15, no. 9, Art. no. 629, 2025, doi: 10.3390/bios15090629.

[46] A. M. Pisoschi et al., "Biosensors for food mycotoxin determination: A comparative and critical review," *Chemosensors*, vol. 12, no. 6, Art. no. 92, 2024, doi: 10.3390/chemosensors12060092.

[47] Z. T. Tsegay, E. Hosseini, T. D'Amore, S. Smaoui, and T. Varzakas, "Biosensing strategies to monitor contaminants and additives on fish, meat, poultry, and related products," *Biosensors*, vol. 15, no. 7, Art. no. 415, 2025, doi: 10.3390/bios15070415.

[48] G. Thenuwara, P. Akhtar, B. Javed, B. Singh, H. J. Byrne, and F. Tian, "Recent advancements in lateral flow assays for food mycotoxin detection: A review of nanoparticle-based methods and innovations," *Toxins*, vol. 17, no. 7, Art. no.

348, 2025, doi: 10.3390/toxins17070348.

[49] X. Cui, T. Gu, K. Ma, J. Zeng, and H. Xia, "Laser-induced graphene electrochemical sensors: An emerging platform for agri-food and environmental detection," *Chemosensors*, vol. 13, no. 12, Art. no. 432, 2025, doi: 10.3390/chemosensors13120432.

[50] C. Albu, A. Chira, G.-L. Radu, and S. A. V. Eremia, "Advances in cost-effective chemosensors for sustainable monitoring in food safety and processing," *Chemosensors*, vol. 13, no. 3, Art. no. 113, 2025, doi: 10.3390/chemosensors13030113.

[51] F. Mateo, E. M. Mateo, A. Tarazona, M. Á. García-Esparza, J. M. Soria, and M. Jiménez, "New strategies and artificial intelligence methods for the mitigation of toxigenic fungi and mycotoxins in foods," *Toxins*, vol. 17, no. 5, Art. no. 231, 2025, doi: 10.3390/toxins17050231.

[52] L. El Hosry and E. Bou-Maroun, "Molecularly imprinted polymer-based sensors in food contaminants analysis: Advances, applications, and future trends," *Chemosensors*, vol. 13, no. 12, Art. no. 420, 2025, doi: 10.3390/chemosensors13120420.

[53] L. Qu et al., "Research progress on nanotechnology-driven enzyme biosensors for electrochemical detection of biological pollution and food contaminants," *Foods*, vol. 14, no. 7, Art. no. 1254, 2025, doi: 10.3390/foods14071254.

[54] K. Lakavath et al., "Progress on electrochemical biomimetic nanosensors for the detection and monitoring of mycotoxins and pesticides," *Toxins*, vol. 16, no. 6, Art. no. 244, 2024, doi: 10.3390/toxins16060244.

[55] J. Sun, M. Zhang, Q. Gao, and B. Shao, "Screening biotoxin aptamer and their application of optical aptasensor in food stuff: A review," *Front. Chem.*, vol. 12, Art. no. 1425774, 2024, doi: 10.3389/fchem.2024.1425774.

[56] Y. Zeng, R. Yuan, H. Fu, Z. Xu, and S. Wei, "Foodborne pathogen detection using surface acoustic wave biosensors: a review," *RSC Advances*, vol. 14, no. 50, pp. 37087–37103, 2024, doi: 10.1039/d4ra06697a.

[57] K. Du, Q. Zeng, M. Jiang, Z. Hu, M. Zhou, and K. Xia, "CRISPR/Cas12a-based biosensing: Advances in mechanisms and applications for nucleic acid detection," *Biosensors*, vol. 15, no. 6, Art. no. 360, 2025, doi: 10.3390/bios15060360.

[58] Y. Sun, T. Wen, P. Zhang, M. Wang, and Y. Xu, "Recent advances in the CRISPR/Cas-based nucleic acid biosensor for food analysis: A review," *Foods*, vol. 13, no. 20, Art. no. 3222, 2024, doi: 10.3390/foods13203222.

[59] H. Turasan and J. Kokini, "Novel nondestructive biosensors for the food industry," *Annual Review of Food Science and Technology*, vol. 12, pp. 539–566, 2021, doi: 10.1146/annurev-food-062520-082307.

[60] E. N. S. Engku Abd Rahman, A. A. Irekeola, N. Y. Yusof, and C. Y. Yean, "Enhancing food safety: a systematic review of electrochemical biosensors for pathogen detection – advancements, limitations, and practical challenges," *Food Control*, vol. 179, Art. no. 111603, 2026, doi: 10.1016/j.foodcont.2025.111603.

[61] S. Savas and S. M. T. Gharibzahedi, "Multiplex nanoparticle-based biosensing for foodborne bacterial pathogens: analytical design, device translation, and real-world validation," *TrAC Trends in Analytical Chemistry*, vol. 202, Art. no. 118921, 2026, doi: 10.1016/j.trac.2026.118921.

[62] M. Techakasikornpanich, K. Jangpatarapongsa, D. Polpanich, N. Zine, A. Errachid, and A. Elaissari, "Biosensor technologies: DNA-based approaches for foodborne pathogen detection," *TrAC Trends in Analytical Chemistry*, vol. 180, Art. no. 117925, 2024, doi: 10.1016/j.trac.2024.117925.

[63] T. A. Bruce-Tagoe et al., "Advances in aptamer-based biosensors for monitoring foodborne pathogens," *Journal of Food Science and Technology*, vol. 61, no. 7, pp. 1252–1271, 2024, doi: 10.1007/s13197-023-05889-8.

[64] N. Eneh, A. Aghaduno, and O. A. Aladegba, "A conceptual framework for integrating aptamer recognition, nanomaterial signal enhancement, and portable detection in food safety biosensors," *Indian J. Environ. Dev.*, vol. 14, no. 2, 2023, doi: 10.21590/ijed.14.2.5.

[65] K. K. Mishra et al., "Next-generation food safety: AI-augmented biosensors for intelligent contaminant monitoring," *Microchemical Journal*, vol. 225, Art. no. 118273, 2026, doi: 10.1016/j.microc.2026.118273.

[66] A. Sophian, "Smart biosensors for Food Safety 4.0: A review," *Journal of Food Safety and Hygiene*, vol. 12, no. 2, 2026, doi: 10.18502/jfsh.v12i2.23050.

[67] W. Guo, M. Jiang, Y. Xie, H. Xu, and Z. Sun, "Recognition element-based strategies for rapid detection of foodborne pathogens: Recent progress and perspectives," *Biosensors*, vol. 15, no. 11, Art. no. 717, 2025, doi: 10.3390/bios15110717.

[68] R. J. S. Banicod, N. Tabassum, D.-M. Jo, A. Javaid, Y.-M. Kim, and F. Khan, "Integration of artificial intelligence in biosensors for enhanced detection of foodborne pathogens," *Biosensors*, vol. 15, no. 10, Art. no. 690, 2025, doi: 10.3390/bios15100690.

[69] E. Xing, H. Chen, X. Xin, H. Cui, Y. Dou, and S. Song, "Recent advances in smart phone-based biosensors for various applications," *Chemosensors*, vol. 13, no. 7, Art. no. 221, 2025, doi: 10.3390/chemosensors13070221.

[70] F. Mi, M. Guan, C. Hu, F. Peng, S. Sun, and X. Wang, "Application of lectin-based biosensor technology in the detection of foodborne pathogenic bacteria: a review," *The Analyst*, vol. 146, no. 2, pp. 429–443, 2021, doi: 10.1039/d0an01459a.

[71] B. C. Jones and M. Ominyi, "Toward a conceptual framework for agricultural export promotion under the African Continental Free Trade Area," *IIARD Journal of Business and African Economy*, vol. 8, no. 1, pp. 88–118, 2022, doi: 10.56201/jbae.v8.no1.2022.pg88.118.

[72] ISO/IEC 17025:2017, "General requirements for the competence of testing and calibration laboratories," Geneva, Switzerland: ISO, 2017.

[73] N. Eneh, K. Abdulrazaq, H. D. Yusuf, and O. A. Aladegba, "Advances in clinical biochemistry laboratory quality assurance: Analytical accuracy, error prevention, and diagnostic reliability," *Indian J. Pharm. Biol. Res.*, vol. 6, no. 4, pp. 55–67, 2018, doi: 10.30750/ijpbr.6.4.11.

[74] N. Eneh, K. Abdulrazaq, H. D. Yusuf, and O. A. Aladegba, "Emerging approaches to quality management in resource-limited clinical laboratories: A critical review of diagnostic reliability and patient safety," *Indian J. Pharm. Biol. Res.*, vol. 7, no. 4, pp. 26–44, 2019, doi: 10.30750/ijpbr.7.4.5.

[75] O. A. Aladegba and M. Ayinde, "From analytical chemistry to

predictive toxicology: A review of data pipelines linking environmental measurement to health prediction," *International Journal of Technology Management & Humanities*, vol. 10, no. 3, pp. 185–216, 2024, doi: 10.21590/ijtmh.10.03.09.

[76] O. A. Aladegba, M. Ayinde, and L. U. Agwuna, "Toward personalized prevention of environmentally induced cancers: A conceptual model coupling exposure biomarkers with individual susceptibility," *Indian Journal of Environment & Development*, vol. 12, no. 1, pp. 1–28, 2021.

[77] O. A. Aladegba, M. Ayinde, and L. U. Agwuna, "AI-enabled early-warning and decision support for environmentally induced cancer in e-waste and automobile-recycling communities: A conceptual public-health framework," *Journal of Contemporary Science and Technology Management*, vol. 1, no. 4, pp. 79–123, 2025.

[78] L. O. Azeez and O. B. Badmus, "Data-driven framework for predicting subsurface contamination pathways in complex remediation projects," *Iconic Research and Engineering Journals*, vol. 2, no. 5, pp. 312–335, 2018.

[79] O. B. A. Lamidi and A. Olamide, "Spatially explicit risk modeling framework for tracking subsurface contaminant migration in data-limited remediation sites," *Iconic Research and Engineering Journals*, vol. 2, no. 6, pp. 178–198, 2018.

[80] F. Bao et al, "Toward intelligent food packaging of biosensor and film substrate for monitoring foodborne microorganisms: a review of recent advancements," *Critical Reviews in Food Science and Nutrition*, vol. 64, no. 12, pp. 3920–3931, 2022, doi: 10.1080/10408398.2022.2137774.

