

THE DIGITAL SENTINEL: REVIEW ON FO, RS AND AI FOR PROACTIVE FOOD-WATER NEXUS RISK

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Abstract. The necessity for sustainable food systems dictates a critical move towards proactive, evidence-based Food Safety and Risk Assessment, particularly in the face of escalating environmental threats. The global proliferation of Harmful Algal Blooms (HABs) poses a major, dynamic risk to water security, which rapidly translates into food contamination. Traditional, reactive testing methods are inadequate for managing this emerging hazard. This Perspective article proposes a unified "Digital Sentinel" framework that transforms environmental surveillance into predictive supply chain alerts. The Sentinel operates by fusing two complementary data streams. First, macro-scale environmental monitoring, accomplished through Remote Sensing platforms, provides continuous geospatial tracking and predictive modeling of bloom intensity. Second, this information is validated by micro-scale molecular insights, utilizing Algal Omics technologies (Genomics, Transcriptomics) for high-throughput identification of toxic species and quantification of toxin-producing genes. Hence, the integration of this heterogeneous data is achieved using advanced Big Data analytics and Explainable Artificial Intelligence (XAI). This intelligent layer generates a verifiable, proactive risk score that informs evidence-based regulatory decisions. Thus, the Digital Sentinel strengthens Food Safety, certifies product origin for Food Authenticity, and fully embodies the principles of Foodomics, Digitalization, and the indispensable One Health Model. Hence, the approach is promising and aligns with the direction of digital transformation in food safety and environmental health.

Keywords: *Artificial Intelligence (AI), digitalization, food authenticity, foodomics, food safety, harmful algal blooms*

Introduction

Achieving resilient global food security is fundamentally reliant on rigorous scientific underpinning and evidence-based decision making. The rising influence of climate change and anthropogenic activity has profoundly destabilized aquatic ecosystems, leading to a marked increase in the frequency and severity of emerging risks. Foremost among these is the escalating global crisis of Harmful Algal Blooms (HABs), which threaten not only environmental health but cascade directly into the food system via contaminated fisheries, aquaculture products, and agricultural irrigation water (Gambhir et al., 2025; Even et al., 2024; Grzybowski and Yahya, 2012). Current approaches to Food Safety and Risk Assessment, often prioritizing endpoint testing of finished products, have proven chronically reactive against the speed and scale of these dynamic environmental threats. A bold conceptual framework is required to bridge the gap between environmental monitoring and food safety certification. This Perspective posits that the solution lies in the digital fusion of macro-scale ecological surveillance with micro-scale molecular hazard assessment, mediated by intelligent computational systems. This proposed "Digital Sentinel" framework directly addresses critical thematic areas within the discourse on sustainable food systems, including Foodomics, Digitalization, Food Authenticity, and the application of the One Health Model (Hassauer and Roosen, 2020; Manzini and Accorsi, 2013). The successful implementation of such a system would fundamentally shift risk management from

mitigation to prediction, providing verifiable data essential for both public health protection and the prevention of economic fraud (Wang et al., 2025; Nwoke, 2024). Therefore, the subsequent sections present a focused hypothesis on how the integration of Remote Sensing, Algal Omics, and Explainable Artificial Intelligence (XAI) can be architected to realize this proactive vision (Alvarez, 2017).

Results and Discussion

Macro-Scale Vigilance: Remote Sensing as the environmental sensor

The initial and broadest layer of the Digital Sentinel must capture the spatial and temporal dynamics of environmental threats. Traditional in-situ water quality monitoring, while accurate, remains too sparse and costly to track phenomena as rapid and vast as HABs effectively Mishra et al. (2025). Hence, the strategic deployment of Remote Sensing technologies is indispensable for providing the necessary synoptic and continuous assessment of aquatic ecosystems (Rabie et al., 2025). This capability aligns precisely with the need for advanced (Bio)sensing, Digitalization & Data Handling in the food system.

Multispectral and hyperspectral platforms

The foundation of macro-scale vigilance rests upon multi-platform satellite observation. Modern missions, such as the European Space Agency's Sentinel series and NASA's MODIS, provide continuous data streams essential for tracking algal parameters (Pinna et al., 2024; European Commission, 2016; Berger et al., 2012). (1) Chlorophyll-a (Chl-a): This is the widely used indicator of algal biomass, retrieved using bio-optical algorithms that analyze the reflectance properties of surface water. Continuous monitoring of Chl-a concentrations provides the primary signal for eutrophication and potential bloom initiation (Assaf et al., 2025). (2) Phycocyanin (PC): Crucially, distinguishing between harmless algae and harmful cyanobacteria requires targeting specific accessory pigments. Phycocyanin is a characteristic pigment found in cyanobacteria (and also in red algae), and its high concentration can serve as a high-fidelity proxy for tracking potentially toxic cyanobacteria species responsible for the most severe harmful algal bloom (HAB) events (O'Shea et al., 2021; Sommer et al., 2021). The power of Remote Sensing lies in its ability to generate vast, time-series Big Data, creating a digital record of water quality that is impossible to achieve through physical sampling alone. This record is the essential precursor dataset for predictive modeling (Santos et al., 2025; Deng et al., 2024).

Challenges in optically complex waters and algorithmic solutions

Nevertheless, the application of Remote Sensing in coastal and inland water termed Optically Complex Waters (OCWs) presents significant technical hurdles. Spectral signals in OCWs are often confounded by non-algal suspended matter (NASM) and colored dissolved organic matter (CDOM), leading to signal interference (Fendereski et al., 2024; Palmer et al., 2015). (1) Algorithmic Refinement: The reliance on simple empirical band-ratios is increasingly giving way to more robust methods. For instance, advanced machine learning models, such as Random Forests and Support Vector Machines, have demonstrated superior performance in accurately retrieving Chl-a and PC concentrations by effectively decoupling the overlapping spectral signatures of co-

occurring optically active components (Wang et al., 2023). (2) Forecasting Models: By incorporating historical satellite data with meteorological and hydrological inputs, predictive models are now capable of forecasting bloom phenology the timing, intensity, and spatial extent with useful lead times. Hence, the macro-scale sentinel provides the warning of where the next contamination front is likely to emerge, moving risk assessment from retrospective to anticipatory (Schaeffer et al., 2024).

Micro-Scale Specificity: Algal Omics as the hazard confirmer

Remote sensing identifies where a potential threat exists; Omics technologies provide the molecular certainty of what that threat is and how severe its potential impact is. This layer directly addresses the core principles of Foodomics, Nutrigenomics & Nutrigenetics as applied to contaminant detection and risk assessment (Ambaru et al., 2025).

Genomics and species identification

The traditional reliance on microscopic taxonomic identification of algae is slow, labor-intensive, and subject to expertise limitations. The transition to molecular methods represents a fundamental advance in bioindicator utility (Medlin and Orozco, 2017). (1) eDNA Metabarcoding: Environmental DNA (eDNA) metabarcoding offers a highly sensitive, non-invasive method for inventorying the entire microbial community within a water sample. This Genomic technique enables the rapid and simultaneous detection of specific toxic taxa, such as those responsible for paralytic shellfish poisoning (PSP) or ciguatera fish poisoning (CFP), even when their cell numbers are low (Hii et al., 2024). (2) Targeted PCR: For high-stakes monitoring, quantitative PCR (qPCR) remains essential for providing absolute quantification of key harmful species or the abundance of their toxin genes (e.g., *mcy* genes for microcystin production or *sxt* genes for saxitoxin). This provides a quantitative measure of hazard concentration, moving beyond mere presence/absence detection (Hii et al., 2024).

Metabolomics and transcriptomics for toxicity assessment

Identifying the species is only half the battle; the true risk depends on whether the cells are actively producing toxins. This physiological state is captured by Metabolomics and Transcriptomics (Otte et al., 2025). (1) Transcriptomics: By measuring the messenger RNA (mRNA) expression levels of toxin biosynthesis genes, Transcriptomics provides a molecular fingerprint of the cells physiological state and its immediate toxic potential. Elevated *mcy* gene transcripts, for instance, serve as a potent early warning biomarker for impending toxicity, often preceding measurable toxin accumulation (Otte et al., 2025). (2) Metabolomics for Contaminant Profiling: Metabolomics, employing techniques like high-resolution Liquid Chromatography/Mass Spectrometry (LC/MS), offers direct, untargeted profiling of the waters biochemical composition. This approach not only quantifies known phycotoxins but also detects emerging contaminants, such as heavy metals or agricultural runoff, which are known to trigger or enhance the toxicity of HABs. The resulting high-dimensional data set is essential for rigorous Food Safety and Risk Assessment (contaminants, toxicity) (Otte et al., 2025). The fusion of genomics (species presence) and metabolomics/transcriptomics (toxicity potential) creates a comprehensive molecular risk profile, transforming the water body into a living biosensor and

generating the high-resolution, micro-scale data required by the Digital Sentinel (Otte et al., 2025).

Digital Fusion: The AI core for predictive risk modeling

The critical challenge is synthesizing the enormous, disparate datasets from Remote Sensing (geospatial time series) and Omics (molecular signatures) into a single, actionable prediction. Artificial Intelligence (AI) serves as the necessary central computational core, aligning with the pressing need for sophisticated Modelling and Data Handling (Zhao et al., 2024).

Architecture for data fusion and predictive scoring

The AI model must be architected to consume multimodal data concurrently. Deep learning architectures, particularly those involving Graph Neural Networks (GNNs) or Convolutional Neural Networks (CNNs) for processing image time-series data, are uniquely suited for this complexity (Zhao et al., 2024). (1) Data Integration Layer: Raw satellite imagery features (e.g., PC intensity, water temperature), along with molecular markers (e.g., mcy gene concentration) and environmental factors (e.g., wind speed, nutrient levels), are vectorized and fed into the model simultaneously (Zhao et al., 2024). (2) Ensemble Prediction: The AI employs an ensemble learning approach to generate a Proactive Risk Score (PRS). This score is a probabilistic forecast of the likelihood that a specific food source (e.g., a shellfish bed or fishing ground) will breach a regulatory safety threshold (e.g., an FDA or EFSA toxin limit) within a specified future time window (e.g., 72 hours) (Zhao et al., 2024). (3) Model Optimization: This sophisticated Modelling capability allows the system to establish complex, non-linear relationships, such as the finding that moderate wind speeds combined with high mcy transcript levels are a stronger predictor of near-shore toxin accumulation than high Chl-a alone (Zhao et al., 2024).

Explainable AI (XAI) for regulatory trust

Scientific rigor demands that models underpinning high-stakes public health decisions are transparent and auditable. Blind reliance on a 'black box' AI model is unacceptable for regulatory and legal contexts, particularly concerning Food Safety (Tjoa and Guan, 2020). (1) Transparency Mandate: Hence, the implementation of Explainable AI (XAI) methodologies is paramount. Techniques such as SHAP (SHapley Additive exPlanations) or LIME (Local Interpretable Model-agnostic Explanations) provide necessary insight (Tjoa and Guan, 2020). (2) Justification of Action: XAI allows the system to output not only the high-risk score but also a breakdown of which features drove that score (e.g., "Risk Score 0.92, driven 60% by Sentinel-3 Phycocyanin anomaly and 30% by confirmed mcy gene expression in adjacent water sample"). This provides the essential, evidence-based justification for authorities to impose fishing closures or modify food processing protocols. Thus, XAI transforms the predictive score from a theoretical warning into a verifiable legal and regulatory instrument (Tjoa and Guan, 2020).

Implications for food system resilience and integrity

The Digital Sentinel framework moves beyond mere monitoring; it fundamentally impacts the operational resilience, integrity, and public health outcomes of the entire food supply chain, fully embracing the One Health Model.

Proactive intervention and food Engineering

The provision of predictive alerts facilitates the transition from costly; reactionary recalls to planned, proactive interventions (Vasileiou et al., 2025; Winkler et al., 2025; Ahmad et al., 2024). (1) Hazard Mitigation: With a specific lead time, food producers and authorities can enact pre-emptive closures of affected harvest zones, divert resources and minimize the exposure of products to contamination. This is a direct application of risk assessment that prevents contamination rather than merely detecting it post-factum (Vasileiou et al., 2025; Winkler et al., 2025; Ahmad et al., 2024). (2) Processing Adjustments: Knowledge of an impending toxic event allows Food Engineering and Technology sectors to adjust treatment protocols. For instance, water treatment facilities can pre-emptively increase adsorption media concentration or switch to alternative disinfection methods (e.g., advanced oxidation processes or non-thermal processing technologies) to ensure the safety of water used for processing or consumption (Vasileiou et al., 2025; Winkler et al., 2025; Ahmad et al., 2024).

Interdicting Fraud: Food authenticity and traceability

Economic disruptions precipitated by environmental instability and food safety crises frequently create powerful incentives for fraudulent activity within supply chains. Advanced surveillance frameworks, functioning as "Digital Sentinels," have emerged as robust deterrents and detection mechanisms against such mislabeling and economic adulteration. Verifiable Origin: This approach employs a dual-layered verification system. The first layer establishes an undeniable geographical record by synthesizing time-stamped remote sensing data with artificial intelligence to delineate environmental risk zones. These AI-generated "risk polygons" map water quality status to specific geographical coordinates. This environmental data is anchored via blockchain technology, enabling regulators and consumers to cross-reference a seafood product's labeled origin against a certified, immutable digital history to confirm it was harvested from a compliant "clean" zone (Duan et al., 2024). Multi-Omics Authentication: The second layer validates the products biological integrity using foodomics technologies, which establish authenticity through geographical origin biomarkers. By integrating environmental risk profiles with the molecular fingerprint of the final product specifically its metabolomic profile, the system can detect chemical inconsistencies. For instance, a fish labeled as originating from a pristine zone but exhibiting metabolic markers consistent with exposure to toxins or pollutants found in "red zones" is flagged as a high-risk indicator of authenticity fraud (Chatterjee et al., 2019). The fusion of these digital and biological data streams creates a guardian security layer that addresses both accidental contamination and deliberate economic adulteration. This synthesis visually and operationally reinforces the One Health model, demonstrating the inextricable link between the health of the external environment and human health outcomes.

Conclusion

The technological blueprint for the Digital Sentinel is largely realized through the synergistic combination of existing and rapidly developing technologies (Remote Sensing, Omics, AI). However, the transition from concept to functional, global infrastructure presents profound policy and implementation challenges. The primary hurdle is the requirement for methodological and data harmonization across international boundaries. (1) Omics Standardization: To ensure global comparability of molecular risk scores, standardized protocols for eDNA and metabolomics sample collection, processing, and bioinformatics pipelines are critical. Differences in primer sets or mass spectrometry settings can lead to non-transferable data, crippling the systems predictive power. (2) Digital Data Sharing: The sheer volume of satellite imagery and omics data requires a centralized, interoperable Big Data infrastructure. This necessitates open-source protocols and regulatory agreements to facilitate the real-time sharing of environmental data between government agencies, regulatory bodies, and industry stakeholders. A failure in timely data exchange will render the system inert.

The adoption of AI-driven risk scores by conservative regulatory bodies (e.g., for fishing closures or product seizure) requires building confidence in the XAI component. (1) Auditable Models: Regulators must move towards demanding 'black box' models to be replaced with transparent, auditable XAI systems, where the mechanism of the risk prediction can be legally and scientifically challenged and verified. (2) Policy Refinement: Current legislation often relies on specific toxin concentration limits in the final product. The Digital Sentinel necessitates policy that can act on a probabilistic risk score—a conceptual shift requiring legislative and judicial groundwork to define the legal sufficiency of a predictive alert. In conclusion, the Digital Sentinel framework provides a viable pathway to achieving proactive Food Safety and verifiable Food Authenticity in an era of environmental instability. Embracing the digital fusion of macro- and micro-scale technologies, the food system can finally move from being a casualty of environmental change to a fully defended, resilient entity, thereby fulfilling the core mandate of a truly sustainable and safe food future.

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Conflict of interest

The authors confirm that there is no conflict of interest involved with any parties in this research study.

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