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Food and Drug Safety

https://ojs.bilpub.com/index.php/fds

ARTICLE

Current Global Trends in Food Safety and Risk Prediction

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ABSTRACT

The study substantiates the shift from traditional reactive control methods to a proactive model of intelligent risk management. Particular emphasis is placed on the "One Health" concept, which integrates human, animal, and ecosystem health within a unified monitoring system; special attention is also given to the destabilizing impact of climate change on food quality and safety—specifically through the spread of mycotoxins and alterations to the planet's microbial landscape. The study provides a detailed analysis of the potential of next-generation sequencing (NGS) for the metagenomic profiling of facilities, the role of nanotechnology in developing precision sensors and active packaging, and the application of Clustered Regularly Interspaced Short Palindromic Repeats (CRISPR)-Cas systems for rapid pathogen diagnostics. Digital architectures for ensuring food safety are examined, with artificial intelligence (AI) and big data analytics presented as key tools for predictive modeling. The data presented address emerging threats such as micro- and nanoplastic contamination, antimicrobial resistance (AMR), and the safety of alternative protein sources. The study demonstrates that systemic contaminants necessitate new approaches to toxicological assessment due to their cumulative effects. It highlights that, by 2026, corporate legal liability will be inextricably linked to digital transparency and the ethics of AI algorithm usage. The study concludes that food safety in 2026 will increasingly depend on the integration of advanced technologies, environmental responsibility, and global digital cooperation.

Keywords: Next-Generation Sequencing; Food Quality and Safety; Reactive Control; Intelligent Risk Management; Antimicrobial Resistance; One Health; Food Industry 4.0

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ARTICLE INFO
Received: 3 March 2026 | Revised: 10 June 2026 | Accepted: 17 June 2026 | Published Online: 24 June 2026
DOI: https://doi.org/10.55121/fds.v3i2.1187

CITATION
Verkhivker, Y., 2026. Current Global Trends in Food Safety and Risk Prediction. Food and Drug Safety. 3(2): 64–80.
DOI: https://doi.org/10.55121/fds.v3i2.1187

1. Introduction

In 2026, the global food industry faces challenges that cannot be solved with the tools of the past decade. Food safety is no longer viewed as a purely technological process limited to the end of the production line—it has become a complex, multi-factorial risk management system that encompasses the biosphere, digital infrastructure, and sociopolitical stability [1,2]. The traditional model, in which inspections were conducted periodically, is increasingly considered outdated due to its reactive nature. The modern paradigm is based on predictive analytics, where risk is identified before the product enters the processing plant [3,4].

The globalization of supply chains has made the system vulnerable. This requires the international community not only to harmonize standards, but to create a single digital space of trust and transparency [5]. As strategic reports note, investments in transparency are no longer viewed solely as compliance costs, but a strategic asset that builds brand value and consumer trust [6].

1.1. Materials and Research Methods

The methodology underlying this review is based on a systemic analysis of the transformation of the global food industry as of 2026. The study examines food safety not as an isolated technological process, but as a multifaceted system integrating the biosphere, digital infrastructure, and sociopolitical factors. The review is grounded in the "One Health" concept, which unifies the monitoring of human, animal, and environmental health into a single integrated framework. The methodology entails an examination of the symbiosis of biological, nanotechnological, and digital tools as the foundational basis for "Food Industry 4.0". Rather than analyzing traditional control methods, the review focuses on proactive risk management models driven by deep learning and multimodal data analysis. It also explores the application of distributed ledger technologies and digital twins to ensure radical transparency and traceability within supply chains.

The following research methods were employed in this study:

Bibliometric analysis: Study of the dynamics of scientific publications on the implementation of AI in the food industry. More than 300 scientific sources were reviewed, of which the 30 most relevant publications were included in the final analysis.

"Digital modeling" approach: Analysis of the effectiveness of recurrent neural networks (RNN) was carried out on the basis of open datasets on pathogen outbreaks in EU countries for 2024–2025.

Comparative microbiological analysis: Comparison of time and resource costs for pathogen identification by classical seeding methods (ISO 6579) and NGS (Next-Generation Sequencing) methods [7,8].

The analysis of active packaging considered composite materials based on biopolymers (Polylactic Acid (PLA), Polyhydroxyalkanoates (PHA)) doped with silver nanoparticles (AgNPs) and zinc oxide (ZnO). The assessment of their antimicrobial efficacy was based on the results of the diffusion method and measurement of the optical density of bacterial suspensions of *Listeria monocytogenes* and *Escherichia coli* [9,10].

1.2. Validation of the Results

The conclusions on the effectiveness of blockchain platforms were verified by analyzing case studies of large retailers (Walmart, Carrefour), which implemented full-scale digital traceability systems to full digital traceability in the first quarter of 2026 [2,11].

2. Discussion

2.1. Philosophy of System Transformation: From Control to Intelligent Management: A Holistic Ecosystem View

One of the cornerstones of modern security policy is the "One Health" approach, formally enshrined in the WHO Global Strategy [4]. This concept emphasizes that human health cannot be separated from the health of animals, plants and the environment.

Microbiome Interdependence: Studies demonstrate that the microbiome of production facilities is a mirror image of the microbiome of personnel and the surrounding ecosystem. Pathogens such as *Listeria monocytogenes* can form persistent biofilms that adapt to traditional disinfection methods, which requires the introduction of new metagenomics analysis methods for their detection [8,12].

The threat of antibiotic resistance (AMR): Food products of animal origin remain a major vector for the transmission of resistance genes from farms to the human population. Monitoring AMR in global meat supply chains has become a major food safety priority as the treatment of foodborne illnesses is becoming increasingly difficult due to the ineffectiveness of standard antibiotics [13,14].

Zoonotic infections: With over 60% of new infectious diseases of zoonotic origin, food safety surveillance is increasingly integrated with early warning systems for epidemics [2].

2.1.1. Climate Destabilization and Its Impact on Food Integrity

The FAO (2024) report "Climate Change: Unpacking the Burden on Food Safety" was a watershed in understanding how the climate crisis is changing the chemical and biological composition of our food [1]. Climate is no longer merely an external environmental factor—it is an active risk factor.

The mycotoxin problem: Global warming has changed the geography of the distribution of mold fungi. Traditionally "safe" northern regions are now facing high levels of aflatoxins and fumonisins in corn and wheat. Predictive modeling based on large-scale climatic data analysis is becoming the only tool to prevent toxic grains from entering the food chain [15].

Marine biotoxins and pathogens: Rising ocean temperatures are stimulating algal blooms and the proliferation of Vibrio bacteria. This poses new challenges for seafood safety, requiring the installation of real-time sensor-based water monitoring systems [16].

Chemical risks and soil: Extreme weather events (floods, droughts) contribute to the mobilization of heavy metals in soils, which are then absorbed by crops. This requires a review of soil safety standards and the implementation of regenerative farming practices [17].

2.1.2. "New Era of Smarter Food Safety": The Digital Revolution as a Response to Chaos

The U.S. Food and Drug Administration (FDA)'s "Smart Safety" concept envisions a transition to a paperless, intelligent, and automated environment [18]. It is not simply automating existing processes, but creating a new digital architecture.

Blockchain and Enhanced Transparency: The use of distributed ledger technologies allows for the creation of a "product passport." In the event of an infection, the path of a product from a specific field to the store shelf can be traced in seconds, allowing for targeted recalls instead of mass destruction of safe food [11].

Artificial Intelligence (AI) and Machine Learning (ML): AI algorithms analyze thousands of variables—from logistics routes to humidity levels in the shop—to detect patterns that are invisible to humans. AI helps automate Hazard Analysis and Critical Control Points (HACCP) compliance checks, enabling continuous real-time monitoring [3,19,20].

Digital Twins: In 2026, large enterprises use digital copies of their lines to simulate crisis situations. This allows them to test the effectiveness of cleaning systems or the safety effects of new ingredients without affecting real production processes [21].

2.1.3. Greening and Sustainability: Safety within Planetary Boundaries

The current paradigm requires resolving the conflict between safety and sustainability. In the past, safety was often achieved through excessive packaging and the use of chemicals; today, the emphasis is shifting to "green" technologies.

Circular economy and waste: UNEP (2025) emphasizes that food waste is not only an economic problem, but also a safety problem. Perishable products become a source of pathogens. Smart distribution systems and dynamic pricing based on expiration dates help minimize these risks [5,22].

Active and intelligent packaging: Instead of passive plastics, biodegradable films with silver nanoparticles or plant extracts that inhibit bacterial growth are used [10,23]. Integrated oxygen scavengers and freshness sensors allow the consumer to see the actual condition of the product, rather than just referring to the printed date [24,25].

Biodegradable sensors: Recent advances in nanotechnology have made it possible to create inexpensive sensors that can be composted with the packaging. They can detect volatile compounds that indicate spoilage of meat or fish at the molecular level [26].

2.1.4. New Consumer Trends and Ethical Aspects

The consumer of 2026 is more informed and demanding than ever before. The trend for transparency has become dominant. People want to know not only about the absence of pesticides, but also about working conditions on farms, the carbon footprint and the origin of each ingredient [27].

Authenticity and the fight against counterfeiting: The use of molecular authentication methods allows protecting premium products from counterfeiting, which is critical for safety, since counterfeits often do not undergo any quality control [28].

Personalized safety: With the development of nutrigenomics, safety standards are starting to take into account individual consumer characteristics, in particular allergens and intolerances to certain ingredients, which requires ultra-precise labeling and separation of production flows.

Thus, the analysis presented here demonstrates that we are living in the era of "Safety by Design". Food safety is no longer a set of hygiene rules; it is an intellectual discipline based on deep data analysis, environmental responsibility, and an understanding of global ecosystem connections. The following sections of this article will detail the technical and analytical tools that make this new paradigm possible.

2.2. Global Trends in Quality and Safety Assurance: Technological Convergence

The current state of the food industry in 2026 is characterized by the final transition from traditional methods of chemical and microbiological analysis to integrated intelligent management systems. This phenomenon, known as "Food Industry 4.0", is based on the fundamental convergence of biotechnology, nanotechnology and digital tools. Such integration allows for an unprecedented level of quality control, moving from static inspections to dynamic monitoring in real time [4,5,18].

2.2.1. Next-Generation Sequencing (NGS) and Metagenomics: Deep Analysis of the Microbiome

One of the most significant technological breakthroughs in recent years has been the introduction of Next-Generation Sequencing (NGS) methods directly into the operational safety management system. Unlike classical methods that require culturing pathogens in the laboratory (which takes 24–72 h), NGS provides a complete genetic picture of the microbial landscape of the enterprise in a matter of hours [7].

Metagenomic profile and enterprise "residents": Studies have shown that each food production facility has its own unique "metagenomic footprint"—a stable collection of microorganisms that form the so-called "Built Environment Microbiome". Analysis of this landscape allows us to identify not only known pathogens, but also risk zones where disinfectant resistance genes can accumulate. This allows us to create individual sanitation protocols aimed at specific "weak spots" in the factory ecosystem [12,18].

Dynamic biofilm prediction: Using metagenomics, it is possible to identify bacteria that may be non-pathogenic in themselves but contribute to the formation of biofilms that harbor dangerous strains of *Listeria monocytogenes* or Salmonella. Understanding these microbial interactions is key to preventing chronic contamination of processing lines [12,18].

High-precision outbreak tracking: With whole-genome sequencing (WGS), regulators in 2026 will be able to link a specific bacterial isolate found in a product on the supermarket shelf with absolute precision to a specific piece of equipment on the other side of the world. This radically increases business accountability and allows the problem to be localized without mass recalls of safe products [2,7] (see **Figure 1**).

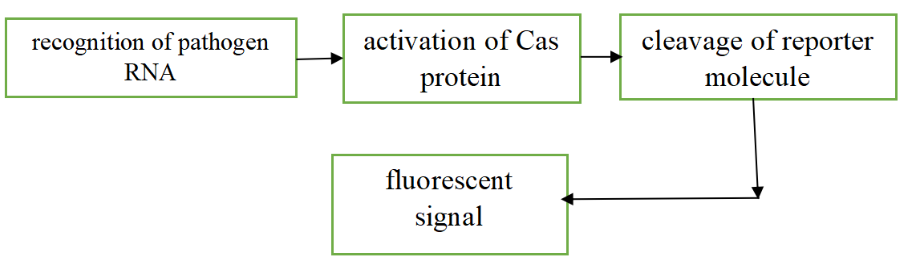

Figure 1. Algorithm of CRISPR biosensor operation in production.

2.2.2. Nanotechnology: Molecular Level of Detection and Active Protection

Nanotechnologies in food supply in 2026 ceased to be experimental and became the standard for packaging and express diagnostics. Their role lies in the creation of an "advanced protective system" around the product [9].

Nanosensors and "Smart Dust": The development of optical nanosensors based on gold nanoclusters and quantum dots makes it possible to detect single cells of pathogens or trace amounts of mycotoxins. These sensors can be part of portable devices or integrated in any way to automatically confirm the cleanliness of surfaces after sanitary cleaning [9,16].

Active antimicrobial packaging and Green Deal: The addition of silver nanoparticles (AgNPs), zinc oxide (ZnO) and titanium dioxide (TiO_2) into the structure of packaging melts inhibits the growth of a broad spectrum of microorganisms. An important aspect is the evolution to "green" nanocomposites—viscous nanocrystalline cellulose and chitosan, which not only protect the product, but are completely decomposed in nature in 30–60 days, so the strategy of the European Green Deal [10,24,29].

Carriers for nutraceuticals: Nanoencapsulation allows you to protect sensitive components (vitamins, antioxidants) from oxidation, immediately ensuring their safe distribution in the body of the patient, which is part of the trend for functional and safe food [9] (see **Figure 2**).

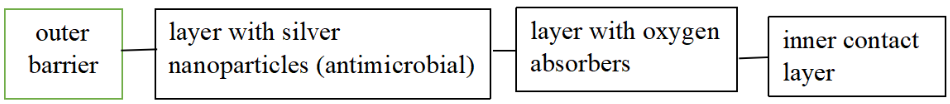

Figure 2. Multilayer structure of active nanopackaging.

CRISPR-Cas genome editing has found its most unexpected application in food risk diagnostics. In 2026, CRISPR-based biosensors will emerge as a faster and more cost-effective alternative to PCR tests. Sherlock and DETECTR in the food industry: These diagnostic platforms use specific proteins, Cas12 and Cas13, which activate a signaling molecule when they find the target pathogen DNA. The result of a test for the presence of, for example, Campylobacter in poultry meat can be obtained in 15–20 min without complex laboratory equipment [30].

Electronic biosensors: The combination of CRISPR with graphene transistors allows the creation of digital interfaces that transmit data on microbial contamination of raw materials in real time to cloud storage of the enterprise's HACCP system. This creates continuous digital traceability record [30,31] (**Table 1**).

Table 1. Technological matrix of safety control methods (2026).

Technology	Detection Object	Analysis Time	Advantages	Limitations
NGS (Sequencing)	Complete microbial genome	12–18 h	Detection of unknown threats	High cost of equipment
Nanosensors	Toxins	Volatile compounds < 5 min	Real-time monitoring	Sensitivity to interference
CRISPR-Cas12/13	Specific DNA/RNA	20–40 min	High selectivity	Requires sample preparation
Cold plasma	Surface pathogens	1–3 min	Chemical-free disinfection	Risk of lipid oxidation

2.2.3. Smart and Intelligent Packaging (Smart Packaging): Interactive Protection

The packaging of 2026 is a combination of materials science and digital communication. It acts as a "last line" that protects the product and at the same time informs about its condition [25,31,32].

Dynamic freshness indicators: Unlike static "use by" dates, modern sensors respond to spoilage metabolites (amines, ethanol, carbon dioxide). If the product has been stored improperly and has started to spoil before the deadline, the package will change color, warning the consumer of the danger [23,26].

Intelligent environmental regulation: A new generation of modified atmosphere packaging (MAP) is able to "breathe". Special membranes regulate the diffusion rate of oxygen and ethylene depending on the ambient temperature, which allows for significantly extending the shelf life of fresh vegetables and fruits without the use of preservatives [23,25].

Near Field Communication (NFC) and blockchain integration: Each item can have an embedded NFC tag that contains a cryptographically protected history of temperature conditions during transportation. The consumer, by touching the smartphone, receives confirmation that the "cold chain" has not been broken for a minute [6,11,27].

2.2.4. Advanced Decontamination Methods: Clean Energy Instead of Chemistry

Traditional chemical food processing methods are gradually being replaced by "cold" decontamination technologies that minimize the impact on organoleptic properties.

Cold Plasma and AOP: Low-temperature plasma treatment of products allows the destruction of bacteria, viruses and even fungal spores on the surface of complex objects (e.g., seeds or nuts). Advanced Oxidation Processes (AOP) based on ozonation and ultraviolet light ensure the sterility of washing water without creating toxic organochlorine compounds [33].

Photodynamic Pathogen Inactivation: This method uses natural light-sensitive substances (photosensitizers), which, under the influence of visible light, produce reactive oxygen species that destroy microbial membranes. This is an ideal solution for organic products, where the use of synthetic chemistry is strictly limited [16,32].

2.2.5. Molecular Authentication: Protecting against Food Fraud

Food fraud is perceived as a national security threat in 2026, as adulterated ingredients often carry hidden toxicity.

Isotopic fingerprinting: A method of analyzing stable isotopes allows you to verify whether honey was actually harvested in a specific region, or whether wine is an authentic product of the declared terroir. This makes it impossible to substitute expensive local products with cheap imports [28].

DNA metabarcoding: For complex multi-component products (e.g., meat semi-finished products or feed), this method allows you to identify the DNA of all biological species in the mixture, detecting undeclared impurities or allergens, which is critical for the safety of sensitive consumer groups [27,28].

Digital verification: Molecular analysis data is automatically uploaded to a quality management system, creating a "digital certificate of authenticity" that accompanies a batch of goods across all borders [6].

2.2.6. Regulatory Challenges and Ethical Aspects

The rapid introduction of nano- and biotechnology requires an updated legislative framework. EFSA (European Food Safety Agency) and FDA are actively developing new protocols for the safety assessment of nanomaterials that can migrate from packaging into food [18,19].

An important trend is also the "ethics of transparency": consumers have the right to know whether genome editing or nanoprocessing methods have been used. This stimulates the development of clear and understandable digital labeling systems that are not misleading, but provide complete information for informed choices [5,27].

Thus, global trends in the field of quality indicate that we have entered the era of "precision food safety". Technological convergence allows for the creation of a multi-layered protection system, where each stage—from the genetic code of the raw material to the molecular composition of the atmosphere in the package—is under constant control. This not only reduces health risks, but also lays the foundation for building sustainable, transparent and ethical food systems of the future.

2.3. Risk Forecasting with AI and Big Data: From Reactive Control to Intelligent Prevention

In 2026, the global architecture of food risk management underwent a fundamental transformation comparable in scale to an industrial transformation. The industry has finally moved away from the outdated "incident detection" model (where control occurred after the fact) to a proactive "intelligent prevention" paradigm. The foundation of this change has become Artificial Intelligence (AI) and Big Data analytics, which allow for identifying threats at the stage of their emergence. As emphasized in the joint reports of EFSA and FDA, digital maturity of safety systems is today not just a competitive advantage, but a basic condition for business legitimacy in the global supply chain [5,18,19].

2.3.1. Artificial Intelligence Architecture in Food Risk Assessment

The introduction of deep learning algorithms has allowed the combination of disparate data streams into a single predictive ecosystem. Modern safety management systems are based on the analysis of multimodal data covering the entire product life cycle.

Cognitive production monitoring: Unlike traditional HACCP, where critical points were monitored periodically, modern neural networks enable continuous monitoring and auditing. Computer vision algorithms analyze video streams from the workshops in real time, monitoring the correct use of personal protective equipment by personnel and the sterility of equipment. Any deviation from the protocol automatically blocks the conveyor, preventing the release of a potentially dangerous batch [4,20].

Neural networks for microbiological modeling: The use of generative models allows scientists to simulate the behavior of bacteria under different conditions (changes in pH, temperature, and humidity). This allows for the development of new product formulations with enhanced intrinsic stability, where the risk of pathogen growth is minimized at the formulation design stage [3,19] (see **Figure 3**).

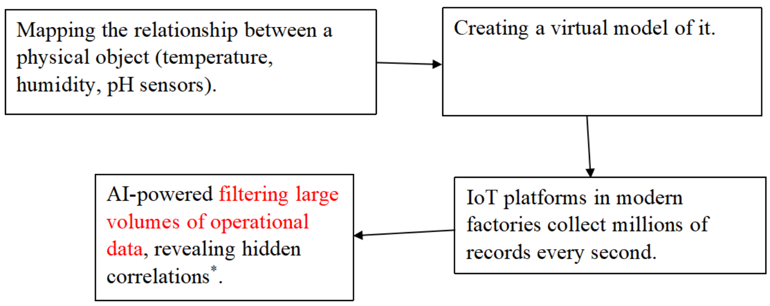

Figure 3. Architecture of the "Digital Twin" of a food product.

Note: * For example, how a slight drop in pressure in an air purification system is associated with an increase in the population of spore-forming bacteria in the finished product after three days [4,31] (see **Table 2**).

Table 2. Effectiveness of AI solutions in the safety management system (KPI) [28].

Indicator (Metric)	Traditional Approach	AI-Integrated Approach	Optimization Level
Traceback	24–72 h	3–10 s	99%
Damage prediction accuracy	70%	95%	25%
Food waste reduction	Baseline	−40% from baseline	40%

2.3.2. Predictive Modeling of Ecosystem Threats and Climate Anomalies

Climate change has transformed risk prediction into chaos. Traditional statistical models no longer work in a world of extreme temperature swings (see **Figure 4**).

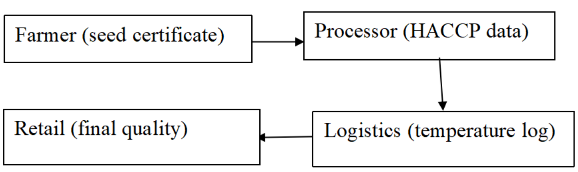

Figure 4. Blockchain traceability chain "from field to table".

2.3.3. Mycotoxicological Risk Modeling

By integrating satellite data with AI algorithms developed with FAO support, it has become possible to create real-time maps of the risk of toxin accumulation. The models analyze not only the current weather, but also the level of plant stress, the phenological phases of crop development and the presence of infection vectors (insects). This allows grain traders to redirect product flows in advance depending on the level of its toxicological profile [14,15,17].

Early Warning Systems: In 2026, global ocean monitoring networks use Big Data to predict “red tides”. AI analyzes a combination of factors: from chlorophyll concentration to water salinity, which allows seafood producers to be warned of the danger several weeks before shellfish are actually infected with biotoxins [16].

2.3.4. The Concept of Digital Twins and Dynamic Security

Digital twins have become a key tool for managing logistics chains that are becoming longer and more complex. A digital twin of a product (e.g., yogurt packaging) accompanies its physical counterpart. If a refrigerator breaks down during transportation, AI instantly calculates how much the shelf life of a particular pallet has decreased. This allows for informed decisions to be made: whether to dispose of the product, send it for recycling, or sell it immediately [21,23].

2.3.5. Resource Optimization and Sustainability

Digital twins allow for modeling the impact of new environmentally friendly packaging materials on product safety. This is critical for the transition to plastic-free production, as it allows for verification that biodegradable films provide the same level of barrier protection as traditional materials [25,26].

2.3.6. Blockchain and Big Data

Shaping a Global Space of Trust Blockchain technology is the “backbone” of food industry information security in 2026. In the event of an incident (such as an *E. coli* outbreak), a blockchain system integrated with retail databases allows for the identification of all points of sale where a dangerous product is located in 2.2 s. According to the IBM food trust report [12], this is thousands of times faster than in 2020, allowing for the localization of the problem within a single store or batch, instead of stopping the entire industry [6,11]. Big data allows for mass comparative analysis of product compositions. If the algorithm sees an anomalous change in the chemical profile of a particular brand of olive oil, the system automatically sends a notification to regulatory authorities for molecular authentication [6,28].

2.3.7. Social Analytics and Digital Epidemiology

In 2026, public opinion and consumer digital activity have become important sources of data for risk prediction. Natural language processing (NLP) algorithms constantly scan social networks and medical forums. Identifying clusters of complaints of similar symptoms (nausea, diarrhea) combined with geolocation data and supermarket receipts allows us to identify the source of infection at a stage when it has not yet entered official hospital reports. This allows us to save thousands of lives by quickly notifying the population [1,4].

2.3.8. Consumer Insights and Reputational Risks

Big Data analysis allows brands to understand consumers’ fears and expectations regarding safety. This incentivizes companies to be more transparent in labeling and processing methods, as any hidden problem instantly becomes public knowledge thanks to digital globalization [27]. With the full digitalization of the industry, a new, previously unknown threat has emerged: cyberattacks on quality management systems. A breach of the HACCP management system can lead to deliberate temperature violations or recipe changes that compromise food system security. In 2026, cybersecurity in food plants is considered part of national security. The use of AI for AI Defense has become a mandatory standard for large corporations [2].

Real-time data verification: To prevent the substitution of quality data in the blockchain, biometric and hardware authentication methods are used at each stage of information entry, ensuring the “purity” of the product’s digital footprint [4,6].

2.3.9. Ethical Challenges and “Explainable AI”

Regulatory bodies such as EFSA and FDA have strict requirements for the transparency of algorithms that make safety decisions.

No black boxes: If an algorithm decides that a batch of milk is unfit for consumption, quality experts should be able to get a clear explanation of what indicators were used to reach this conclusion. This is necessary to avoid erroneous decisions and to ensure trust on the part of producers [5,19].

Harmonizing digital standards: The UN and the World Trade Organization are working to create common data exchange protocols so that AI systems from different countries can communicate seamlessly with each other, ensuring global food safety [5].

Thus, it should be noted that risk prediction using AI and Big Data has transformed food safety into a dynamic, high-tech discipline in 2026. The integration of digital twins, predictive analytics and blockchain has allowed the creation of intelligent risk-prevention framework for the global food system. This not only ensures the highest level of protection of human health, but also allows building sustainable economic models where resource losses are minimized and consumer trust is based on proven facts, not on marketing promises.

2.4. New Threats and Sources of Danger: From Microplastics to Alternative Proteins

The evolution of global food systems in 2026 is accompanied by the emergence of new, previously poorly understood risk categories that require a fundamental revision of classical approaches to toxicology and microbiology. While traditional pathogens (such as Salmonella, Campylobacter or Listeria) are currently relatively well managed with digital traceability systems and automated lines, threats arising at the nanoscale or due to radical changes in raw material sources require the development of fundamentally new methodologies for safety assessment. As noted in the UNEP and EFSA reports, we have entered the era of "systemic contaminants" that have long-term cumulative effects on human health, but are often ignored due to the lack of rapid clinical manifestations [10,19,22].

2.4.1. The Micro- and Nanoplastic Epidemic: The Molecular Level of Pollution

Plastic pollution has evolved from a visual environmental problem to a critical threat to food security. In 2026, the scientific community is focusing not only on the mechanical presence of plastic particles in food, but also on their ability to alter biochemical processes in the consumer's body (see **Table 3**).

Table 3. Systemic risk profile of emerging food threats.

Threat Type Source	Mechanism of Impact	Regulatory	Priority
Nanoplastic	Packaging, water	Cellular inflammation	Critical
Cultured protein	Lab-grown meat	Genetic drift of cells	Average
AMR genes	Meat, vegetables	Horizontal transfer	High
Mycotoxins 2.0	Cereals	Synergistic toxicity	High

Vectors of systemic infiltration: Microplastics are now found in a wide range of products, from sea salt and seafood to drinking water, honey and the tissues of terrestrial animals. The most concerning category is nanoplastic (particles <1 μm in size). Due to their tiny size, they are able to cross the blood-brain barrier, cross the placenta and accumulate in parenchymal organs, potentially contributing to chronic cellular inflammation [10,22,29].

Plastic as a sorption agent: Plastic particles have the ability to adsorb persistent organic pollutants (POPs), pesticides, dioxins and heavy metals on their surface. Thus, by consuming a product with microplastics, a concentrated mixture of hazardous contaminants. These compounds have a cumulative effect and can act as endocrine disruptors, disrupting the hormonal balance of the consumer [10,29] (see **Figure 5**).

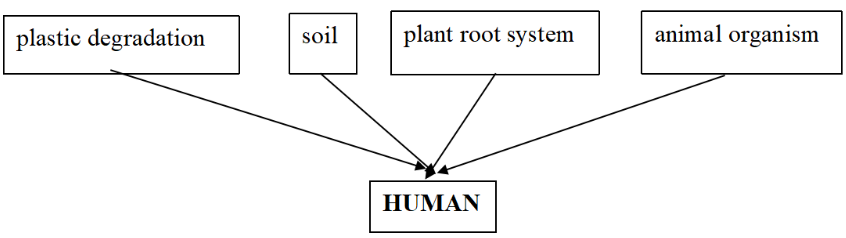

Figure 5. The cycle of circulation of microplastics and nanoplastics in the agrosphere.

The accumulation of microplastics in agricultural lands (due to the use of wastewater and plastic films) changes the structure of soil microflora. This leads to a disruption of the nitrogen and phosphorus cycle, which affects plant immunity and contributes to the accumulation of specific phytotoxins that were previously not considered significant for safety [17,29].

2.4.2. Safety of Alternative Protein Sources: Technological and Biological Risks

The global shift to alternative proteins (Novel Foods), driven by sustainable development strategies, has created a whole new set of challenges for regulators. Creating imitation meat or dairy products requires the use of complex technological processes, each of which has its own risk zones. Cultured (cellular) meat: The safety of this product depends on the absolute sterility of reactors and the chemical purity of cell culture media. The main risks are the potential presence of residues of growth factors, hormones and synthetic antibiotics used to maintain the vital activity of cell lines. A separate issue is the genetic stability of cells: with multiple divisions, there are risks of mutations, the consequences of which for humans are still being studied [7,30].

2.4.3. Visualization of Plasmid Transfer between Bacteria in a Food Product and the Human Gut Microbiome

Entomoproteins (edible insects): The use of insects as food faces the problem of cross-allergenicity. Insect proteins (in particular tropomyosin) are very similar to those of crustaceans and house dust mites, which can cause acute anaphylactic reactions in a significant part of the population. In addition, insects are able to accumulate heavy metals (cadmium, lead) and pesticides from substrates, which requires the implementation of strict GFSI standards for their industrial cultivation [27,33].

Fermentation proteins (mushroom and algae): The production of mycoproteins requires precise control over the absence of “wild” strains of fungi in fermenters, which can produce dangerous mycotoxins. Also relevant is the issue of controlling the content of nucleic acids in the final product, since their excess can lead to an increase in uric acid levels in consumers [15,28].

2.4.4. Climatic Migration of Pathogens: Reshaping the Biogeography of Risks

As highlighted in the FAO report, climate change is a powerful driver of the transformation of microbiological threats. We are observing the phenomenon of “thermal adaptation” of pathogens, which become more resistant to cooking [1].

Expanding the ranges of marine pathogens: Due to warming of the world’s oceans, the bacteria *Vibrio parahaemolyticus* and *Vibrio vulnificus* (traditionally tropical pathogens) have begun to actively colonize oyster farms in the North Atlantic and the Baltic Sea. This requires the introduction of high-pressure processing (HPP) technologies for products that were traditionally consumed raw [1,16,32].

New transmission vectors: Changes in humidity and temperature facilitate the migration of insect pests and rodents that are vectors of zoonotic infections. This creates new routes for infection of agricultural lands previously considered safe and requires a review of HACCP plans in crop production [2,17].

Fungal synergy: Under climatic stress, plants become vulnerable to simultaneous attack by multiple fungal species. This leads to the appearance in the grain of combinations of mycotoxins (e.g., deoxynivalenol + zearalenone) that enhance the toxic effects of each other, even if the concentration of each individually is within normal limits [14].

2.5. Nanoparticles in Packaging and "Smart Packaging": The Downside of Innovation

Although nanotechnology offers excellent antimicrobial protection, there is a serious risk of migration of nanomaterials directly into the food product.

Particle migration phenomenon: Studies indicate that silver and titanium oxide nanoparticles can separate from the polymer matrix of the packaging when exposed to fatty acids or high acidity of the product. Silver nanoparticles have the ability to disrupt the balance of beneficial intestinal microflora (microbiome), which can lead to digestive disorders and reduced immunity in the consumer [12,24,25].

Chemical transformation of active ingredients: Active packaging that releases antioxidants or essential oils may react with food ingredients during microwave heating, forming new compounds with unknown toxicological profiles [23,29].

2.6. Antibiotic Resistance (AMR): The Food Chain as a Reservoir of Resistance Genes

In 2026, antibiotic resistance is recognized as a "silent pandemic," with food serving as a major conduit for superbugs.

Horizontal gene transfers: The danger is not only from living resistant bacteria. Even after heat treatment, DNA fragments (plasmids) carrying resistance genes can remain in meat. These fragments can be taken up by bacteria in the human body, turning normal microflora into drug-resistant ones [12,13].

Global regulatory disparities: While the EU and the US have severely restricted the use of antibiotics as growth promoters, the practice continues in developing countries. Due to the globalization of trade, meat products with high levels of AMR enter global markets, undermining the efforts of developed countries to combat this threat [2,4,11].

2.7. Food Fraud 2.0 and Digital Counterfeiting

Food crime in 2026 has evolved to a high-tech level, using advances in chemistry and IT.

Molecular mimicry: Counterfeiters have learned to create chemical mixtures that mimic the profile of expensive products (such as honey or olive oil) so accurately that standard purity tests are ineffective. To detect such counterfeits, sophisticated isotope analysis and high-resolution mass spectrometry are now required [25,26,29].

Cyber-manipulation and "Digital Food Fraud": The use of generative AI to create fake safety certificates and hacking blockchain systems to legalize low-quality raw materials are new types of threats that require the involvement of cyber police in food safety control [5,14,34].

2.8. Challenges of Biodegradable Packaging and Sustainability

The greening of the industry, while a positive trend, has created new risks for storage safety. Premature decomposition and spoilage: Starch- or cellulose-based bioplastics are hygroscopic. If humidity is disturbed in the warehouse, the packaging can begin to decompose prematurely, losing its barrier properties and creating a favorable environment for the growth of mold fungi and the development of insect pests [30,34,35].

Toxicity of degradation products: The use of new additives to accelerate the degradation of plastic can lead to the migration of these substances into food, which requires a thorough toxicological assessment of each new type of biodegradable material by regulatory authorities [33,35].

Thus, the analysis of new threats in 2026 confirms that food safety has become a multidisciplinary problem, where environmental risks (microplastics), biotechnological innovations (alternative proteins) and climate change are intertwined. The main challenge of the future is not just the detection of known pathogens, but also understanding the synergistic effect of different pollutants on the human body. Future quality management systems should be based on the principle of "precautionary precaution", where any innovation (new packaging or protein source) undergoes rigorous predictive testing for safety for future generations.

2.9. Regulatory Policy and International Standards: From Formal Control to Digital Transparency

In 2026, the regulatory environment in the field of food safety has undergone the most radical changes in the last three decades. The dynamic development of AI technologies, the emergence of alternative proteins and critical climate challenges have forced international institutions such as ISO, Codex Alimentarius and GFSI to reconsider the fundamental principles of standardization. Modern regulatory policy is based on the concept of "Data-Driven Governance", where state supervision ceases to be an external check and becomes an integrated component of the digital systems of the enterprise [3,7,31].

2.9.1. Digital Transformation of ISO 22000 and HACCP: From Paper to Algorithms

Classical food safety management systems (FSMS) have evolved from paper protocols into dynamic digital ecosystems. The update of the ISO 22000 series of standards, version 2025–2026, reflects the transition to continuous verification.

Real-time HACCP: Traditional risk analysis, which was carried out annually, has been found to be ineffective in a changing environment. The new requirements of the standards require enterprises to implement predictive algorithms that automatically calculate critical limits depending on the current humidity, temperature or microbiological profile of the input raw materials. Artificial intelligence has become an essential tool for validating these changes, which allows for eliminating the delay between risk detection and system response [14,19,20].

Legal validity of digital records: Legislation in most developed countries now equates automatic records from Internet of Things (IoT) sensors with official documents. Any attempt to manipulate data in cloud storage is considered falsification of reporting, which forces companies to invest in cyber protection of their management systems [2,6,11].

Food Safety Culture as an audit indicator: Regulators have officially included the socio-psychological factor in mandatory requirements. Assessment of how staff understand the values of safety is now carried out using behavioral data analysis: the frequency of hand washing is monitored via smart cameras and the accuracy of sanitary regulations, which is reflected in the enterprise's digital safety rating of the enterprise [27,34]. The WHO Global Strategy for Food Safety 2022–2030 has set strong guidelines for national governments to integrate food surveillance into the overall national food safety and health system [4].

Institutional convergence: The 2026 standards require producers to be fully transparent with veterinary and environmental authorities. This is necessary to create an "ecological safety perimeter" around production, allowing for the rapid detection of threats from antibiotic resistance and zoonotic infections at the farm level [1,2,13].

Regulation of the microbiome of manufacturing facilities: Regulators have begun to mandate that facilities monitor their metagenomes. If NGS (next-generation sequencing) detects resistant strains of pathogens in a facility, the regulator may suspend the safety certificate even if the finished product is clean, as a preventative measure against future outbreaks [8,12] (see **Figure 6**).

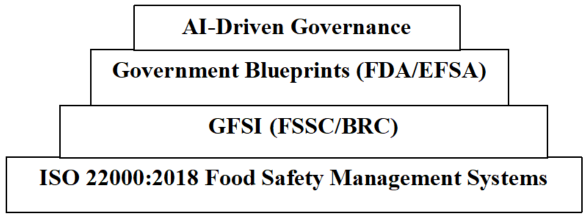

Figure 6. Global regulatory compliance pyramid.

2.9.2. GFSI 2025.1: New Certification Requirements and Smart Audits

The Global Food Safety Initiative (GFSI) has introduced the concept of "continuous certification" in its updated Benchmarking Requirements, which effectively eliminates the concept of "annual audit" in favor of continuous monitoring [7].

Hybrid audits and Augmented Reality (AR) technologies: The use of augmented reality glasses and inspection drones allows auditors to conduct virtual inspections of facilities anywhere in the world. This eliminates geographical barriers and allows for surprise inspections without lengthy approvals, which increases the objectivity of the assessment [5,34].

Blockchain standardization: The GFSI now recognizes data from certified blockchain platforms as primary evidence of traceability. Businesses that cannot provide a digital footprint of a product from farm to shelf automatically receive a lower trust rating, limiting their access to premium markets [6,11].

2.9.3. Regulation of Alternative Proteins: The Legal Vacuum Is Filled

Creating a legal framework for Novel Foods has become a priority for regulators in 2024–2026. Regulation of cultured meat: The EU and the US have introduced parallel certification systems for cell products. The requirements focus on the safety of the culture media and the absence of uncontrolled mutations in the cell lines. Each batch of cultured meat must have a molecular passport confirming its identity and safety [5,7,30].

Entomoproteins and novel allergens: Mandatory "Cross-Reactivity" labeling has been introduced. Regulators require insect meal manufacturers to conduct precision tests for chitin content and specific proteins that can cause allergies similar to those to seafood [10,29].

2.9.4. Digital Compliance and the FDA's Blueprint for the Future

The FDA's "New Era of Smarter Food Safety" has evolved from an experimental plan to a comprehensive digital regulatory framework that being followed by the world's leading economies [3].

- **Automated Key Data Elements (KDE) Submission**

The new rules require critical traceability event data to be submitted to government registries in a machine-readable format. This allows government agencies to conduct automated risk screening across the country, identifying anomalies in supply chains before affected consumers contact them [3,12,32].

- **Algorithmic Oversight**

Government inspectors are now using AI systems to score businesses for risk. Factories with low digital scores (frequent sensor failures, opaque supply chains) are five times more likely to be physically inspected than digitally transparent companies [3,9,25].

2.9.5. Environmental Legislation and the Green Deal: Safety vs. Sustainability

In 2026, the concept of a "safe product" officially includes the environmental safety of its packaging.

- **Regulation of Migration from Bioplastics**

The European Commission has set new limits for substances migrating from biodegradable materials. Manufacturers must use mass spectrometry methods to prove that corn- or seaweed-based packaging does not release potentially toxic degradation metabolites into the product [35]. Ban on "forever plastic" in food contact: Heavy fines have been introduced for the use of packaging containing PFAS (perfluorinated compounds), which were previously used to protect against grease. Regulators are demanding a transition to certified nanocoatings with proven safety for the human endocrine system [22,33].

- **Ethics of Artificial Intelligence and Transparency of Algorithms (Explainable AI)**

With the increasing role of AI in decision-making, the question of legal liability for algorithm errors has arisen.

Neural network auditing: Regulators (including EFSA) are requiring companies to provide a "blueprint" for AI algorithms. Any decision to recall or allow a product to enter the market made by a machine must be interpretable by a human. This prevents "black box" situations where the reasons for rejecting a product batch remain unclear [9,25,31].

- **Data Protection and Cyber Resilience**

The 2026 standards equate cybersecurity of a food plant with physical security. Businesses are required to regularly stress-test their HACCP systems against hacker attacks, as temperature manipulation via the network can be a tool for bioterrorism [26,28].

- **International Trade and "Green Corridors" of Security**

In 2026, food safety became a key factor in the formation of new trade alliances.

Digital equivalence: Countries are moving towards the recognition of "digital security certificates". If an exporter provides full access to its blockchain and real-time monitoring data, its products pass through customs under a simplified "green corridor" procedure, which is critical for perishable products [19,31,32].

Combating "toxic dumping": International agreements now include sanction mechanisms against countries that export products produced using antibiotics or pesticides banned in developed countries, which levels the playing field for ethical producers [4,26,31].

Thus, regulatory policy in 2026 has finally transformed from a reactive tool of punishment to a proactive system of precision management. The harmonization of ISO standards, WHO strategies and GFSI requirements has created a global digital safety net. The main challenge for business has become the need for full transparency —in 2026 it is impossible to be "a little safe". Companies that invest in digital compliance and ethical production receive not only consumer loyalty, but also direct preferences from the state and access to global markets. The future belongs to those who perceive security standards not as restrictions, but as the language spoken by the modern global economy.

3. Conclusions

A comprehensive analysis of the state and prospects for the development of the global food quality and safety assurance system in 2026 allows us to draw the following final conclusions:

Technological convergence as a new foundation for security. The study confirmed that the era of isolated analytical methods has largely come to an end. Modern security is based on the synergy of biotechnology (NGS, CRISPR), nanotechnology and digital tools. This made it possible to move from static control of the final product to dynamic management of the microbiome of the entire production environment. The introduction of nanosensors and active packaging created an additional "intelligent barrier" that minimizes the impact of the human factor.

Digital transformation and predictive analytics. The integration of artificial intelligence and Big Data has significantly improved the speed of risk response. The use of "digital twins" and blockchain platforms has provided a level of traceability at which the identification of the source of the threat in the global supply chain has been reduced from days to seconds. Predictive modeling, especially in the areas of mycotoxicology and climate threats, allows for neutralizing risks at the stage of primary production. Adaptation to new systemic threats. The work revealed that microplastics, antibiotic resistance (AMR) and the safety of alternative proteins (cultured meat, entomoproteins) are the major emerging challenges of the decade. It was established that these threats have a transboundary and cumulative nature, which requires the development of new international standards for toxicological assessment and decontamination methods (cold plasma, photodynamic inactivation).

Evolution of regulatory compliance: The regulatory policies of leading institutions (EFSA, FDA, WHO) have finally shifted towards "digital surveillance". The update of ISO 22000 standards and GFSI requirements emphasizes the priority of "food safety culture" and transparency of AI algorithms. In 2026, consumer trust and access to markets directly depend on a company's ability to provide verified digital proof of safety at every stage of the product's life cycle.

Strategic vector: sustainability and transparency. The final analysis proves that the future of the food industry lies in the plane of the "One Health" concept. Food safety is no longer considered in isolation from the ecological state of the planet and the health of ecosystems. Only through global cooperation, open data exchange and the implementation of ethical technologies will humanity be able to build a sustainable food system that can withstand the challenges of climate change and the growing demographic burden.

In summary, the analysis shows that in 2026, the food safety system will transform from a reactive control model into a comprehensive digital risk management ecosystem. The key trend is the integration of artificial intelligence, Big Data, biotechnology and digital traceability into a single predictive security mechanism. It has been established that modern risks are systemic in nature and are formed under the influence of climate change, globalization of supply chains, the spread of antibiotic resistance, micro- and nanoplastics, as well as the emergence of alternative protein sources. This necessitates the transition to the "One Health" concept, within which product safety is considered in relation to the state of the environment, animal and human health. It has been proven that NGS technologies, CRISPR biosensors, digital twins and blockchain not only increase the speed of threat detection, but also form a new level of transparency and manageability of food systems. At the same time, digitalization creates new challenges—cybersecurity dependency, ethical risks of AI algorithms, and the need for harmonization of international digital regulation. Therefore, the future effectiveness of the global food security system will not be determined by individual technological solutions, but by the ability of states, businesses, and international institutions to integrate environmental, biotechnological, and digital approaches into a single, sustainable risk management model. Besides, it can be argued that food safety in 2026 has evolved from a cost-related component of business operations into its main strategic asset. Investments in intelligent control systems today are one of the key factors ensuring long-term competitiveness and preserving the health of the global population.

Funding

This work received no external funding.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

Not applicable.

Conflicts of Interest

The author declares no conflict of interest.

AI Use Statement

The author declares that no artificial intelligence (AI) tools were used in the preparation of this manuscript.

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