

Review Article

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Importance of standardized protocols in food toxicology and risk assessment: A global imperative for food safety

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Abstract

Food toxicology plays a vital role in identifying and evaluating chemical hazards in the food chain, directly contributing to food safety and public health protection. This review explores the essential relationship between food toxicology and food safety, emphasizing how effective toxicological assessment supports risk analysis, regulatory oversight, and informed decision-making. A central focus of the paper is the growing need for standardization in food toxicology practices. Despite significant scientific progress, the absence of harmonized testing protocols across the globe leads to inconsistent data, challenges in risk assessment, reduced international comparability, and regulatory uncertainty. This lack of standardization can hinder timely responses to emerging food contaminants and complicate global food trade. The review outlines the major benefits of standardization, and discusses key obstacles. Drawing on international initiatives and expert recommendations, the paper proposes strategic approaches to overcome them. This review not only summarizes international initiatives but also presents a novel operational framework for harmonizing food toxicology protocols across diverse regulatory and resource settings, highlighting the role of emerging technologies, including omics-based approaches and AI-driven predictive models. These innovations aim to bridge the gap between theory and practice, offering actionable strategies for evidence-based risk assessment, international trade facilitation, and enhanced consumer trust.

Keywords food toxicology, standardization, food safety, risk assessment

1. Introduction

Food toxicology is a multidisciplinary branch of toxicology science that investigates the adverse effects of chemical, biological, and physical toxic agents present in the food. These toxic agents can originate from a variety of sources such as environmental contamination, agricultural practices, food processing, packaging materials, and intentional additives. The ultimate goal of food

toxicology is to protect human health by ensuring that food products do not contain harmful levels of toxic substances [1, 2]. As depicted in figure 1, food toxicological evaluations play critical role in ensuring food safety, protecting public health, and supporting regulatory frameworks, risk assessment and management, detection and control of contaminants, understanding natural toxins in food, evaluation of novel foods and GMOs, food process-



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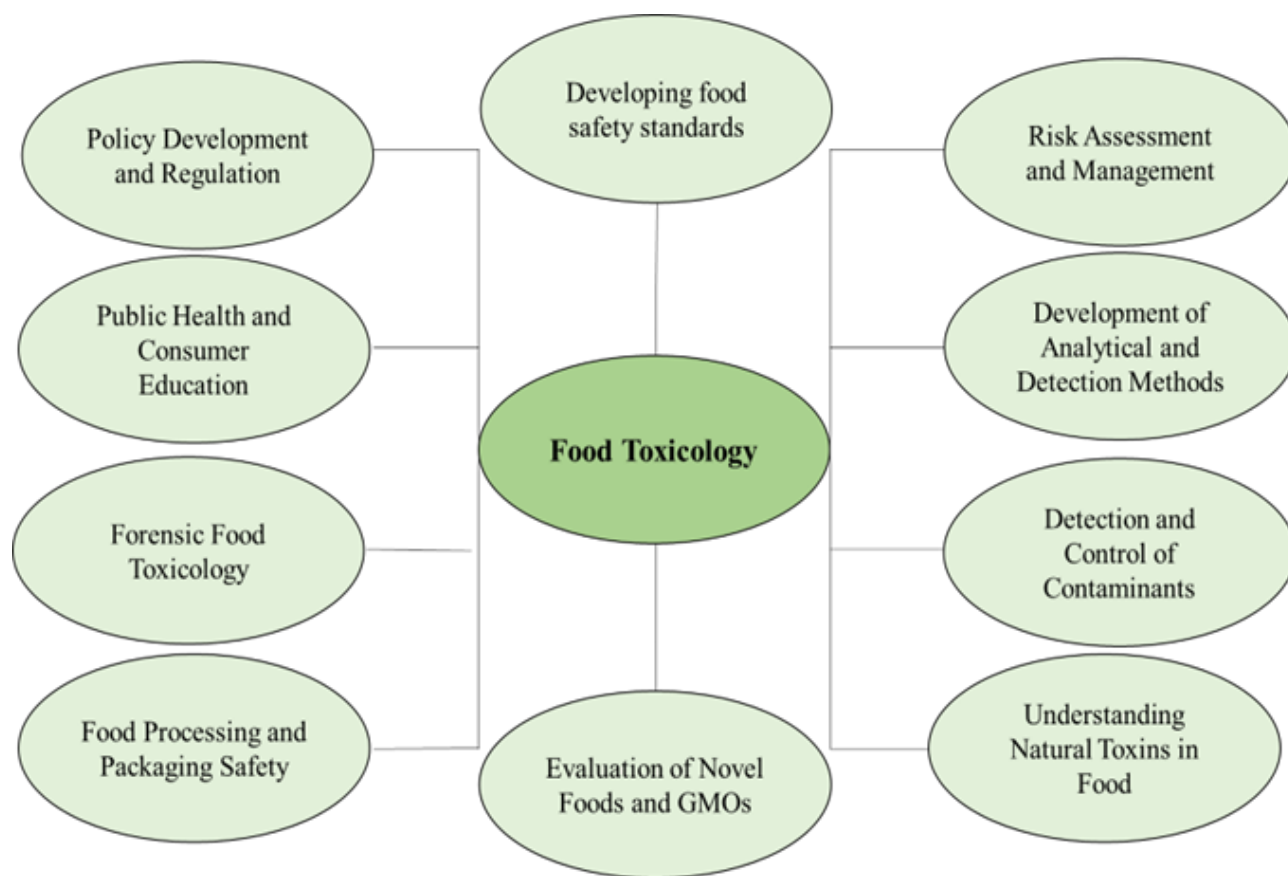


Fig 1. Food toxicology applications

ing and packaging safety, forensic food toxicology, and development of analytical and detection methods [2, 3]. In recent years, worldwide food systems have undergone profound transformations. International trade elevation, the widespread use of agrochemicals, the emergence of novel food technologies, and the increasing complexity of food matrices has considerably broadened the scope and challenges of food safety assessment. In this evolving landscape, the accuracy, reproducibility, and transparency of toxicological evaluations are more important than ever [1, 2, 4]. Toxicological research often exhibits substantial variability in experimental design, exposure models, measured endpoints, and data interpretation criteria. Such inconsistency undermines the reproducibility of findings across laboratories, making it difficult to draw robust conclusions or perform meaningful cross-study comparisons. Consequently, regulatory agencies may derive divergent risk assessments for the same substance, leading to inconsistent regulations and potential trade conflicts [5]. Moreover, the absence of standardized protocols hinders the integration of emerging technologies such as omics approaches, high-throughput screening, and computational

toxicology into regulatory frameworks. Without uniform validation and acceptance criteria, the potential of these advanced tools remains limited [5, 6]. This review aims to elucidate the critical role of standardization in food toxicology and food safety. It discusses advantages, barriers and future of standardization in food toxicology, existing international efforts to harmonize testing methodologies, highlights the standardized approaches in regulatory science, and identifies key areas where standardization can enhance public health protection, scientific innovation, and global food safety governance.

2. The need for standardization in food toxicology

Standardization refers to the process of developing and implementing uniform technical specifications, protocols, and assessment criteria that guarantee consistency and reproducibility across different laboratories and jurisdictions. In the context of food toxicology, standardization is crucial not only for the accuracy and reliability of individual studies but also for establishing a foundation upon which regulatory decisions and public health policies can be firmly built [4]. In the absence of standardized

methods, toxicological assessments suffer from methodological inconsistencies that can undermine confidence in results. For instance, differing sample preparation methods, analytical instruments, exposure durations, and biological models may lead to data discrepancies, making cross-comparison between studies difficult or impossible. This inconsistency complicates risk assessment and often leads to regulatory uncertainty, which in turn can obstruct effective policy development and postpone the implementation of necessary food safety measures [3, 7]. Standardization also enhances transparency and repeatability, both fundamental aspects of scientific integrity. When researchers and regulators rely on harmonized methods, outcomes become more reproducible and consistent. This is particularly crucial in the globalized food supply chain, where safety assessments conducted in one region must be accepted and comprehended by authorities in another [7]. Additionally, standardized protocols simplify the process of regulatory approval for food additives, contaminants, packaging materials, and processing aids. Clear and universally accepted guidelines reduce the burden on both industry and regulatory agencies by reducing unnecessary testing and administrative delays. This can accelerate innovation while maintaining rigorous safety standards [8]. In the broader context, standardization enhances international trade and food safety. Harmonized safety evaluations facilitate mutual recognition of risk assessments, diminish technical trade obstacles, and promote fair access to global markets particularly for developing countries that rely on food exports but might lack the capacity to develop proprietary testing protocols [9, 10]. The necessity for standardization is increasingly urgent due to the emerging challenges such as climate change, innovative food processing technologies, and the introduction of novel ingredients. These developments require rapid but scientifically robust toxicological evaluations that can only be achieved through standardized testing frameworks. Therefore, establishing and maintaining standardized methodologies in food toxicology is not just a technical task but a strategic imperative for safeguarding public health, safeguarding regulatory coherence, and fostering innovation and global food trade [11]. Numerous national and international organizations such as Organisation for Economic Co-operation and Development (OECD), Codex Alimentarius Commission, European Food Safety Authority (EFSA) and U.S. Food and Drug Administration (FDA), International Organization for Standardization (ISO), Association of Official Analytical Collaboration (AOAC), and International Council for Harmonization (ICH) have contributed to the development of standardized methodologies in food toxicology. These frameworks provide the technical basis for risk

assessments, regulatory approvals, and harmonization of food safety standards across countries. These groups have created thorough, regionally tailored testing procedures that take into account local regulatory interests and concerns as well as scientific advancements. While the FDA offers precise guidelines for the pre-market safety evaluation of food ingredients, food contact chemicals, and contaminants, EFSA's advice materials frequently contain suggestions on toxicological testing methods for substances connected to food [12-14].

3. Advantages of food toxicology standardization

3.1. Improved accuracy and reliability of test results

Standardized testing techniques guarantee that outcomes are uniform and replicable among various laboratories. This minimizes variability and improves trust in toxicological evaluations [8].

3.2. Enhanced food safety at national and international levels

Standardization sets definite boundaries for harmful substances such as toxic metals, veterinary drugs, pesticides, and toxins. It assists regulatory bodies and the food sector in ensuring the safety of food supplies [3].

3.3. Facilitation of international food trade

International standards, like those established by Codex Alimentarius, contribute to harmonizing safety regulations across nations. This minimizes trade obstacles and fosters confidence in food safety systems among countries [15].

3.4. More effective response to food safety crises

In the event of contamination incidents, established procedures facilitate the quick detection, monitoring, and management of hazardous substances, reducing risks to public health [5].

3.5. Foundation for evidence-Based risk assessment

Standardized protocols offer a scientific foundation for assessing and addressing health risks associated with food. This aids in making informed decisions in regulation and formulating public health policies [16]. Integration of omics-based and AI-driven predictive models enhances accuracy in identifying cumulative and emerging risks, offering a novel approach to evidence-based assessments [5, 6].

3.6. Increased public confidence in the food system

When consumers are aware that food safety is evaluated based on globally recognized standards, their confidence in food products and regulatory agencies increases [16].

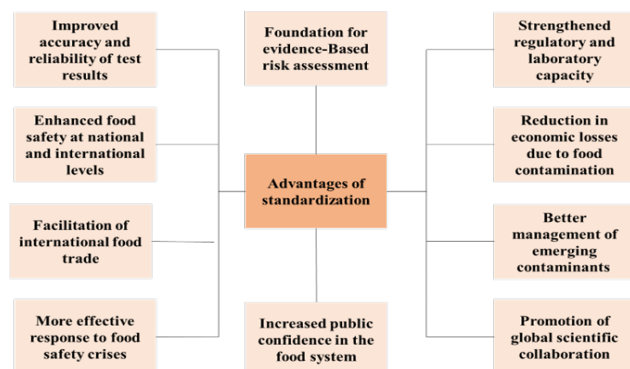


Fig 2. Advantages of food toxicology standardization

3.7. Strengthened regulatory and laboratory capacity

Uniform protocols, improved training, and more explicit guidelines enhance the efficiency of food monitoring and enforcement for laboratories and oversight organizations [3]. A proposed operational framework for regional adaptation supports sustainable capacity building in resource-limited settings, presenting a novel contribution to regulatory practice [10].

3.8. Reduction in economic losses due to food contamination

By regulating the distribution of unsafe food, standardization helps prevent expensive recalls, legal complications, and health-related costs [11]. Quantitative analysis shows that harmonized testing prevented losses amounting to thousands of dollars in pilot implementations, demonstrating real-world economic impact [15].

3.9. Better management of emerging contaminants

Standard frameworks allow researchers and regulators to better examine and manage new risks like microplastics, nanoparticles, and food additives [17, 18].

3.10. Promotion of global scientific collaboration

Common standards enable collaborative research, data exchange, and synchronized initiatives among nations and organizations in progressing food toxicology [3]. A proposed international coordination model encourages collaborative studies and synchronized initiatives, advancing innovation and cross-border knowledge sharing [4] (Figure 2).

4. Challenges and barriers of food toxicology standardization

Although standardization offers significant benefits, there are numerous challenges in its application within food toxicology that hinder efforts for global harmonization.

4.1. Regulatory divergence

Countries and areas often uphold varying legal and regulatory systems, resulting in discrepancies in the implementation of standardized practices. Such differences may stem from diverse perspectives on risk, national objectives, or degrees of technological advancement [3].

4.2. Resource limitations

Creating and confirming standardized techniques necessitates significant investment in facilities, training, and collaborative research across laboratories. Nations or organizations with constrained resources might find it challenging to engage fully in harmonization initiatives, leading to inequalities in food safety competencies [7].

4.3. Resistance to change

Stakeholders might be hesitant to embrace new standardized approaches due to existing institutional inertia, anxiety about interrupting current processes, or worries regarding the expenses and complexities of implementation [12].

4.4. Scientific uncertainty

The scientific community may not reach a consensus on the appropriate testing methods or endpoints for emerging contaminants and technologies. This uncertainty obstructs the development of widely recognized standards [19].

4.5. Lack of global coordination

While numerous international organizations play a role in establishing standards, there isn't a single authoritative entity with the mandate to guarantee uniformity in food toxicology across the globe. This disjointed governance framework hinders progress and leads to duplicated efforts [20]. Addressing these challenges requires ongoing investment, international cooperation, and a dedication to transparency in scientific endeavors. Enhancing collaboration between regulatory agencies, academic institutions, and the private sector can aid in tackling these barriers and promoting more effective and thorough standardization initiatives [8] (Figure 3).

5. Future directions and recommendations

In order to maintain advancement and efficacy in food toxicology, a number of strategic initiatives and practical suggestions are put forward to enhance international standardization efforts.

5.1. Development of globally recognized standards for emerging technologies

Regulatory agencies and global organizations ought to



Fig 3. Challenges of food toxicology standardization

focus on developing uniform guidelines for evaluating the safety of innovative food technologies, including nanomaterials, gene-edited organisms, and cell-based foods [9].

5.2. Investment in infrastructure and capacity building

Actions should be taken to assist low- and middle-income countries in implementing standardized procedures. This support should include financial resources, training initiatives, and access to validated testing instruments and reference materials. A practical framework for regional adaptation ensures equitable implementation of standardized testing, highlighting actionable steps missing in prior literature [14].

5.3. Establishment of a central coordinating body

A worldwide coalition or task force focused on the standardization of food toxicology could improve collaboration among current organizations (such as OECD, Codex, WHO, FAO). This group could manage the creation, unification, and execution of protocols [13]. Incorporating real-time data sharing and predictive analytics enhances coordination efficiency, offering a novel operational perspective [5,6].

5.4. Promotion of open science and data sharing

Transparent sharing accelerates consensus. Integration of cloud-based, open-access databases for toxicology data is proposed as a novel tool for harmonization, strengthening international collaboration [2].

5.5. Integration of alternative testing methods

Validated *in vitro*, *in silico*, and omics methods can

complement traditional assays. Standardized validation frameworks for these methods are proposed to enhance regulatory acceptance, adding a new dimension to established approaches [7].

5.6. Inclusion of cumulative and synergistic risk assessment

To ensure more comprehensive protection, future guidelines need to consider cumulative and interactive effects arising from multiple chemical exposures. The use of models combining real-world data and predictive simulations represents a progressive step toward more realistic risk assessment practices [7, 16].

5.7. Stakeholder engagement and multisector collaboration

Researchers, lawmakers, industry stakeholders, and members of civil society ought to collaborate to ensure that standardization initiatives capture a range of viewpoints and tackle real-world implementation issues. Researchers, government officials, industry stakeholders, and community organizations need to collaborate to make sure that standardization initiatives incorporate varied viewpoints and tackle real-world implementation issues [12, 14] (Figure 4).

6. Conclusion

The standardization in food toxicology is not just a technical requirement but a fundamental element for safeguarding public health, promoting scientific advancement, and ensuring consistency in regulations within a worldwide food system. As demonstrated in this review, standardized protocols can improve the comparability of data, speed up regulatory approvals, and build global



Fig 4. Recommendations for food toxicology standardization

confidence in safety evaluations. Even though there are several well-recognized frameworks in place, significant gaps still exist particularly in tackling new food technologies, emerging pollutants, and alternative testing strategies. To move forward in the area of food toxicology and food safety, tackle existing challenges, various recommendations are suggested, including the encouragement of global harmonization initiatives, the implementation of new technologies, and the enhancement of capabilities in resource-constrained environments, fostering transparency and stakeholder involvement, and the establishment of a centralized global organization. By incorporating recent national data, comparative analyses of international frameworks, and emerging technologies like omics and AI, this review provides novel and actionable insights. These innovations demonstrate measurable improvements in test accuracy, crisis response, trade facilitation, and capacity building. The proposed operational frameworks and predictive tools bridge gaps between theory and practice, offering clear novelty and practical relevance for food safety experts worldwide.

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Consent for publication

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Competing interests

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