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Mercury Contamination in Foods: Public Health Challenges and Policy Recommendations

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Abstract

Background and Objective: Mercury as a toxic contaminate may enter food chains, accumulate in seafood, and pose significant risks to human health. Mercury exposure has been associated with neurological, developmental, renal, and immune disorders, particularly among vulnerable populations such as pregnant women, fetuses, and children. Despite increasing evidence regarding the adverse health effects of mercury, a comprehensive understanding of the molecular mechanisms underlying mercury toxicity and their implications for public health policy remains limited. This study aimed to evaluate the public health implications of mercury contamination in food products and propose evidence-based policy recommendations to reduce mercury exposure and improve food safety.

Methods: Mercury-associated genes and anxiety disorder–related genes were obtained from publicly available biological databases and integrated to identify shared molecular targets. Functional enrichment analyses were conducted to characterize the biological processes and signaling pathways associated with these genes. Gene interaction networks were subsequently constructed and analyzed to identify key regulatory genes and functional relationships. In addition, network pharmacology and molecular docking approaches were used to evaluate potential protective compounds targeting mercury-responsive molecular pathways.

Results and Conclusion: Mercury exposure was found to induce oxidative stress, neuro-inflammation, and dysregulation of inflammatory signaling pathways involving IL1B, IL6, TNF, and IFNG. Evidence also indicated that mercury-responsive genes are enriched in pathways related to inflammation and immune regulation. Based on these findings, policy recommendations were developed focusing on enhanced food safety monitoring, biotechnology-based detection systems, environmental source control, mercury bioremediation, public education, and continued research investment. Mercury contamination should be recognized not only as an environmental issue but also as an important food safety, biotechnology, and public health priority requiring coordinated multidisciplinary action.

Keywords: Mercury, Food Safety, Heavy Metals, Biosensors, Bioremediation

1. Introduction and statement of the problem

Heavy metals are well-known environmental pollutants and represent critical risk factors for human health. They are released through industrial activities such as mining, smelting, and manufacturing, as well as agricultural practices and urban waste, which lead to contamination of soil, water, air, and food chains [1, 2]. Mercury is one of the most toxic heavy metals and poses significant risks to human health. It can enter aquatic ecosystems and accumulate in organisms. Additionally, seafood and dental amalgam fillings are other important sources of human mercury exposure [3]. Long-term mercury exposure disrupts neurological, renal, digestive, and immune functions [4-6]. Recent advances in food biotechnology, including biosensors and rapid detection platforms, offer tools for monitoring mercury contamination in food products and strengthening food safety systems [7]. Therefore, understanding mercury contamination in foods is essential for improving food safety, protecting vulnerable populations, and developing biotechnology-based prevention and remediation strategies.

Contamination with toxic elements is one of the most concerning and challenging issues in this century [8]. These toxic elements enter the food chain in different ways, such as through environmental contamination of food products, waterways and oceans, which are polluted by untreated municipal and industrial wastes, and the rainwater that is contaminated by polluted air [8, 9]. Evidence showed that fish and seafood, which are kinds of marine organisms, contain high concentrations of toxic elements, such as mercury, that can accumulate in human tissues and lead to neurological impairment, developmental abnormalities, and cognitive dysfunction, especially in sensitive populations such as pregnant women, fetuses, and children [9-11]. To evaluate the impact of mercury accumulation in foods on public health and develop effective preventive strategies, it is necessary to understand its mechanisms and consequences. This issue is not only environmental but also technological and regulatory. Conventional monitoring methods may be costly, centralized, and slow, limiting rapid detection across the food supply chain [12]. Therefore, food biotechnology approaches should be integrated into food safety systems to enable faster screening of mercury contamination in seafood and other high-risk products.

2. Methods

Anxiety disorder–related genes were collected from GeneCards, DisGeNET, and DISEASES databases, and overlapping genes were identified using Venn diagram analysis. Mercury-responsive genes were subsequently extracted from the Comparative Toxicogenomics Database (CTD), and common genes between anxiety disorder and mercury-associated datasets were selected as mercury-responsive genes in anxiety disorder. Functional enrichment analysis of these genes was performed using DAVID to identify significantly enriched Gene Ontology (GO) biological processes and KEGG pathways. Protein–protein interaction (PPI) data were obtained from the STRING database and imported into Cytoscape for network construction and topological analysis. Core subnetworks and hub genes were identified using the CytoNCA and CytoHubba plugins. The resulting critical gene network was further analyzed using GeneMANIA to predict gene interactions and functional associations. Finally, potential protective agents against mercury-induced anxiety were identified through network pharmacology approaches, and molecular docking analysis was performed to evaluate the binding interactions between candidate compounds and core target proteins [13].

3. Results

Studies have shown that mercury exposure induces various disorders, including neurotoxicity, nephrotoxicity, genotoxicity, and cardiovascular disturbances. This metal could cross the blood–brain barrier (BBB) and lead to different neurological dysfunctions. Neuroinflammation is considered one of the major contributors to neurological disorders and can be induced through oxidative stress processes [10, 14]. Mercury exposure increases the generation of reactive oxygen species (ROS) and produces oxidative stress. These processes lead to cellular damage and disruption of normal physiological functions. Excessive ROS generation may damage proteins, lipids, and DNA, leading to alterations in cellular metabolism and tissue injury [15]. In addition to oxidative stress, mercury exposure can activate inflammatory pathways and dysregulate cytokine signaling. Functional enrichment and network analyses further demonstrated that mercury-responsive genes are significantly enriched in inflammatory response pathways and the positive regulation of gene expression. Protein–protein interaction (PPI) network analysis identified IL1B, IL6, TNF, and IFNG as core mercury-associated targets, highlighting the central role of inflammatory signaling in mercury toxicity. Additional network-associated genes, including CASP1, TNFAIP3, and SQSTM1, were also linked to mercury-responsive pathways. Furthermore, pathway enrichment analyses identified associations with IL-17 signaling, inflammatory bowel disease, and lipid and atherosclerosis pathways, suggesting contribution of mercury exposure to systemic inflammatory processes beyond neurological dysfunction. Potential protective agents, including quercetin, curcumin, selenium, glutathione, and succimer, were identified because of their antioxidant, anti-inflammatory, and metal-chelating properties, indicating possible therapeutic strategies to mitigate mercury-induced toxicity [13].

4. Health Policy Framework

4.1. Enhanced Food Safety Monitoring and Regulatory Oversight

Regulatory agencies should strengthen surveillance programs for mercury contamination in seafood and other high-risk food products. Routine monitoring should be expanded, particularly for foods frequently consumed by pregnant women, children, and other vulnerable populations. Updated dietary guidelines and seafood consumption advisories should be developed based on current scientific evidence to help consumers make informed dietary choices. In addition, stricter regulatory oversight is needed to ensure compliance with mercury safety limits throughout food production and distribution systems.

4.2. Integration of Food Biotechnology into Mercury Detection Programs

Governments should promote the incorporation of food biotechnology into national food safety frameworks. Investment in the development and validation of biosensor-based detection systems, molecular monitoring tools, and other rapid screening technologies would improve the identification of mercury contamination in seafood and food-processing facilities. Compared with conventional laboratory-based testing, these technologies can facilitate faster detection, support real-time monitoring, and strengthen traceability across the food supply chain.

4.3. Environmental Source Control and Mercury Bioremediation

Prevention of mercury contamination should focus on reducing environmental releases at their source. Policymakers should strengthen industrial discharge regulations, wastewater treatment requirements, emission controls, and environmental monitoring programs for mining, manufacturing, and other mercury-emitting industries. In contaminated ecosystems, bioremediation approaches should be evaluated as sustainable and environmentally friendly remediation strategies. The use of mercury-resistant microorganisms, algae, and plants may help remove, transform, or immobilize mercury in contaminated soil and water, thereby reducing its bioavailability and limiting its entry into aquatic food webs and the human food chain.

4.4. Public Education and Risk Communication

Public health authorities should implement comprehensive educational initiatives to increase awareness of mercury exposure risks and promote safer food choices. Risk communication strategies should be culturally appropriate, scientifically accurate, and tailored to vulnerable populations, including pregnant women, children, and communities with high seafood consumption. Educational campaigns should emphasize both the nutritional benefits of seafood and the importance of selecting low-mercury alternatives to reduce health risks while maintaining dietary quality.

4.5. Research and Innovation in Mercury Prevention Technologies

Policymakers should support interdisciplinary research initiatives aimed at improving mercury monitoring, prevention, and remediation technologies. Continued investment in biotechnology-based detection systems, environmental bioremediation strategies, and food safety surveillance platforms will facilitate the development of more effective and sustainable approaches for reducing mercury contamination. Strengthening collaboration among researchers, public health agencies, environmental regulators, and industry will be essential for translating scientific advances into practical public health solutions.

5. POLICY

Mercury contamination in food products is a serious public health problem because it can enter food chains, accumulate in seafood, and expose humans. Evidence shows that mercury may disrupt neurological and immune functions and may contribute to developmental and cognitive problems. Reducing mercury exposure requires coordinated action through environmental controls, food monitoring, public education, dietary guidance, biotechnology-based detection, and bioremediation. Overall, mercury contamination should be considered not only an environmental issue but also an important food safety, biotechnology, and public health priority.

6. DECLARATIONS

6.1. Acknowledgement

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6.2. Conflict of Interest

All authors declare no conflict of interest.

6.3. Using chatbots:

ChatGPT (OpenAI) was used to assist with language editing, grammar correction, and improvement of manuscript structure. All scientific content, interpretation of findings, and final manuscript revisions were reviewed and approved by the authors.

6.4. Authors' Contributions

The author contributed to literature review, policy recommendation development, manuscript writing, revision, and final approval of the manuscript

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آلودگی جیوه در مواد غذایی: چالش‌های بهداشت عمومی و توصیه‌های سیاستی

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چکیده

سابقه و هدف: جیوه به عنوان یک آلاینده سمی می‌تواند وارد زنجیره‌های غذایی شده، در غذاهای دریایی تجمع یابد و خطرات قابل توجهی را برای سلامت انسان ایجاد کند. قرار گرفتن در معرض جیوه با اختلالات عصبی، رشدی، کلیوی و ایمنی، به ویژه در میان جمعیت‌های آسیب‌پذیر مانند زنان باردار، جنین و کودکان مرتبط بوده است. علیرغم افزایش شواهد در مورد اثرات نامطلوب جیوه بر سلامت، درک جامع از مکانیسم‌های مولکولی زمینه‌ساز سمیت جیوه و پیامدهای آنها برای سیاست‌های بهداشت عمومی همچنان محدود است. این مطالعه با هدف ارزیابی پیامدهای بهداشت عمومی آلودگی جیوه در محصولات غذایی و ارائه توصیه‌های سیاستی مبتنی بر شواهد برای کاهش قرار گرفتن در معرض جیوه و بهبود ایمنی مواد غذایی انجام شد.

روش‌ها: ژن‌های مرتبط با جیوه و ژن‌های مرتبط با اختلال اضطراب از پایگاه‌های داده بیولوژیکی در دسترس عموم جمع‌آوری و برای شناسایی اهداف مولکولی مشترک ادغام شدند. تجزیه و تحلیل‌های غنی‌سازی عملکردی برای توصیف فرآیندهای بیولوژیکی و مسیرهای سیگنالینگ مرتبط با این ژن‌ها انجام شد. متعاقباً شبکه‌های تعامل ژنی ساخته و تجزیه و تحلیل شدند تا ژن‌های تنظیمی کلیدی و روابط عملکردی شناسایی شوند. علاوه بر این، از رویکردهای فارماکولوژی شبکه‌ای و داکینگ مولکولی برای ارزیابی ترکیبات محافظ بالقوه که مسیرهای مولکولی پاسخگو به جیوه را هدف قرار می‌دهند، استفاده شد.

یافته‌ها و نتیجه‌گیری: نتایج نشان داد که مواجهه با جیوه موجب استرس اکسیداتیو، التهاب عصبی و اختلال در مسیرهای پیام‌رسانی التهابی شامل IL1B، IL6، TNF و IFNG می‌شود. همچنین ژن‌های پاسخ‌دهنده به جیوه در مسیرهای مرتبط با التهاب و تنظیم ایمنی غنی‌شدگی قابل توجهی نشان دادند. بر این اساس، راهکارهای سیاستی شامل تقویت پایش ایمنی مواد غذایی، توسعه فناوری‌های تشخیص مبتنی بر زیست‌فناوری، کنترل منابع آلودگی، استفاده از روش‌های زیست‌پالایی، آموزش عمومی و حمایت از پژوهش و نوآوری پیشنهاد شد. آلودگی جیوه باید علاوه بر یک چالش زیست‌محیطی، به‌عنوان یک اولویت مهم در حوزه ایمنی غذایی، زیست‌فناوری و بهداشت عمومی مورد توجه قرار گیرد.

واژگان کلیدی: جیوه، ایمنی مواد غذایی، فلزات سنگین، حسگرهای زیستی، زیست پالایی