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The Economic Importance of Pesticides: Drivers of Residue Emergence in Food and the Need for Rapid Detection Techniques in Africa

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ABSTRACT: Pesticides are essential in modern farming for increase crop yields and ensuring food security and safety. However, their widespread use has resulted in the buildup of pesticide residues in food products, posing serious public health risks, particularly in Africa. This review explores the economic factors driving pesticide use, the causes of residue accumulation, and the urgent need for rapid detection techniques. With a focus on the African context, the paper underscores the significant implications of pesticide residues for food safety and public health, and the pressing need for effective monitoring systems. The excessive use or improper application of pesticides to satisfy the increasing food demand in Africa frequently results in pesticide residues in food. This situation poses significant public health risks through the food chain. Consequently, there is an urgent need for rapid, multi-analyte analysis methods that can detect pesticide residues, serving as effective screening tools for monitoring food safety. The development of quick, convenient, and accurate methods for the detection and quantification of pesticide residues is of utmost importance. This review emphasizes the economic significance of pesticides and the need for advanced analytical methods to quantify residual pesticide concentrations in food.

INTRODUCTION

Agriculture serves as the cornerstone of many African economies, significantly contributing to GDP, employment, and livelihoods. The increasing reliance on pesticides has become essential for enhancing crop yields and protecting against pests and diseases, which is crucial for ensuring food security across the continent. With Africa's population currently around 1.3 billion and expected to double by 2050, there is significant pressure

on food production systems that are already facing low productivity. As the global population is projected to reach 8 billion by 2025 and 9 billion by 2050, the demand for food will continue to rise, requiring an increase in agricultural output. As a result, the use of pesticides is likely to grow to meet these escalating food needs.

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The advantages of pesticide use in Africa are considerable, including enhanced agricultural yields that have improved nutrition, increased household income, and supported both local and international trade. [3]. Furthermore, pesticides play a crucial role in controlling vectors that transmit diseases such as malaria, which remains one of the world's deadliest diseases [4]. Despite these advantages, the widespread use of pesticides also presents serious health risks. Since their introduction by colonial powers, the use of pesticides has steadily increased particularly herbicides and insecticides. It is estimated that a significant proportion of consumed food in Africa is contaminated with pesticide residues, raising significant concerns about food safety and public health [5].

The World Health Organization estimates that around 3 million cases of acute pesticide poisoning occur worldwide each year, leading to approximately 220,000 deaths annually. A significant number of these incidents happen in developing countries, especially in Africa. In these regions, exposure to organophosphates is common, and pesticides are linked to numerous health issues, including cancer, heart disease, Alzheimer's, and Parkinson's disease. Acute exposure to high pesticide doses can be fatal, while long-term exposure may increase cancer risk and disrupt the reproductive, immune, endocrine, and nervous systems. [8]. As household demands for food are projected to increase significantly, the consumption of pesticides is expected to rise, further exacerbating health risks due to repeated dietary intake of pesticide-contaminated foods [9].

Although pesticides are essential for safeguarding crops, their adverse effects on the environment and human health must not be ignored. Global pesticide use has grown significantly, with a substantial portion of these chemicals often being excessive, uneconomic, or unnecessary [9]. For instance, food tests conducted in Nigeria revealed the presence of DDT, Aldrin, and Dieldrin at levels above the maximum allowable concentration, raising public health concerns [10].

The livestock sector is vital to the socioeconomic development of Africa, representing an important source of quality animal protein. In Nigeria, the livestock sector contributes significantly to the total protein intake [11]. However, animal feed is often contaminated with

pesticide residues, which can be transferred to livestock tissues, leading to potential food safety concerns [12]. While the chemical residues in meat and offal resulting from feeding are unlikely to represent a significant health concern, they can disrupt trade if they do not meet export market standards [13].

While pesticides and veterinary drugs play a vital role in enhancing food production and supporting aquaculture, their improper or excessive use can result in residues in food. This highlights the necessity for effective and rapid detection methods to monitor food safety and protect public health in Africa. Many African countries face significant challenges due to the lack of surveillance programs for monitoring pesticide residue levels and the absence of toxicovigilance systems for documenting poisoning cases. Weak or nonexistent regulations, coupled with limited awareness of pesticide hazards among users, further increase the risks associated with pesticide use. Without appropriate regulations and sufficient training for farmers, Africa faces the threat of widespread pesticide poisoning, emphasizing the urgent need for comprehensive strategies to address these risks. [17].

In conclusion, while pesticides are essential for enhancing agricultural productivity and ensuring food security in Africa, their misuse poses significant health and environmental risks. Creating rapid and dependable detection methods for pesticide residues is essential for protecting public health and ensuring food safety throughout the continent. To alleviate the negative impacts of pesticide use and safeguard vulnerable populations from potential health risks, comprehensive strategies involving improved regulation, education, and monitoring are required.

Status of pesticide residues in Africa: distribution among farmers

Human activities have resulted in the extensive spread of pollutants and waste across the environment. Currently, around 6 million chemical compounds have been produced worldwide, with approximately 1,000 new chemicals being developed each year. Among these, between 60,000 and 95,000 chemicals are actively used in commercial applications. [18]. A significant portion of these substances includes chemical pesticides, which are

extensively employed in agricultural practices across Africa.

Pesticides play a crucial role in crop production by minimizing pest infestations, safeguarding crops from yield losses, and ensuring the quality of agricultural products. Nonetheless, the extensive use of these chemicals has raised concerns regarding the buildup of pesticide residues in the environment and food supply. This issue is especially pertinent in Africa, where the distribution and application of pesticides among farmers can differ significantly, often shaped by factors like access to education, resources, and regulatory oversight. Recent studies have highlighted the persistence of pesticide residues in African ecosystem such as soils, water bodies, and farming products, posing significant risks to public health and ecosystem. For instance, research by [19] revealed high levels of pesticide residues in vegetables sold in Ghanaian markets, exceeding the maximum residue limits (MRLs) set by international standards. Similarly, a study by [20] in Burkina Faso found that farmers frequently use pesticides without adequate protective equipment, leading to direct exposure and contamination.

The extensive use of chemical pesticides, while essential for protecting crops, also presents significant challenges, including potential health risks to farmers, consumers, and the broader ecosystem. A study by [21] reported that pesticide poisoning is a growing concern in Tanzania, with farmers often unaware of the dangers posed by improper handling and application. The distribution of pesticide residues among African farmers underscores the urgent need for increased awareness, better regulation, and the promotion of safer and more sustainable agricultural practices. This is vital not only for protecting human health but also for preserving the integrity of the environment and ensuring long-term food security on the continent.

Factors influencing pesticide residues in food

Epidemiological studies show that the improper use of animal drugs in feed, along with the presence of pesticides, industrial chemicals, and natural toxins like aflatoxins, can result in harmful residues in edible tissues, milk, and eggs. Contamination can occur through various pathways, such as the accidental mixing of

pesticides or industrial waste into feed, poor storage of feed and chemicals, and the application of pesticides on crops meant for animal consumption. Additionally, animals may be exposed to contaminants by rummaging through trash containing discarded chemicals, drinking water contaminated by pesticide runoff or industrial waste, and having direct contact with insecticides in their surroundings.

Recent years have seen multiple incidents of harmful residues in food animals due to persistent chemicals from unexpected sources. These incidents can range from single cases involving one producer to widespread issues impacting many producers across large regions. While persistent chemical residues may not pose as immediate a threat to public health or economics as those from natural toxins, feed additives, or drugs, their presence is alarming. This is primarily because such residues are unforeseen by all stakeholders, as these chemicals are generally not linked to conventional agricultural practices [18]. Additionally, their stability makes them difficult to remove, even if they can be detected early.

In Nigeria and several other African countries, the animal production sector is vital, with the use of drugs for growth promotion and disease prevention being common in confined rearing systems. While most animals raised for slaughter are kept in confinement, some are allowed to graze over larger areas. This confinement raises the risk of disease outbreaks, which leads to the sub-therapeutic use of drugs. However, it's crucial that these drugs are used in accordance with specified withdrawal times before slaughter, allowing animals to eliminate any residues before entering the food supply. Issues arise when producers and feedlot operators neglect these withdrawal periods or ignore label instructions, resulting in contamination.

Contaminants from chemicals and pesticides tend to be more easily detectable early on. Technological advancements and strict regulations can help reduce these risks. If producers and feedlot operators strictly follow label instructions and observe proper withdrawal periods, the environment should remain free from such contamination. Additionally, vigilance is necessary to prevent the unintentional introduction of industrial pollutants like polychlorinated biphenyls (PCBs),

polybrominated biphenyls (PBBs), dioxins (TCDD), and other halogenated hydrocarbons.

The public generally perceives persistent chemicals as a greater threat than other potential chemical residues because of their long-lasting effects. When guidelines are adhered to, meat products are processed in facilities that are routinely inspected by regulatory bodies like the National Agency for Food and Drug Administration and Control (NAFDAC). At the retail level, these products should be free from contamination, and if stored and prepared properly, they should remain uncontaminated.

Toxicity and risk associated with pesticide residues in food

Studies on the health impacts of pesticides have primarily focused on those with occupational exposure, including farm workers and pesticide applicators. Acute poisoning from organophosphate (OP) pesticides can result in serious symptoms like nausea, abdominal cramps, diarrhea, dizziness, anxiety, and confusion. Fortunately, these symptoms are typically reversible with suitable medical intervention. () . In contrast, chronic low-dose exposure to pesticides, even among those who do not experience acute poisoning, has been associated with a variety of health issues. These health concerns include respiratory issues, memory disorders, skin problems, depression, miscarriages, birth defects, cancer, and neurological disorders such as Parkinson's disease. A study with a nationally representative sample found a significant link between high levels of organophosphate (OP) pesticide metabolites in urine and an increased likelihood of attention deficit disorder (ADD) or attention deficit hyperactivity disorder (ADHD) in children aged 8 to 15, highlighting the potential risks of pesticide exposure outside of occupational settings [12].

While pesticides are designed to control pests, they can also pose considerable risks to humans, animals, and beneficial plants. Some pesticides are extremely toxic, with even small amounts capable of causing lethal effects in humans. Almost any pesticide can lead to illness if a person is exposed to a sufficient quantity, and even those deemed relatively safe can cause irritation to the skin, eyes, and nose. Understanding how pesticides enter the body is essential for reducing exposure. They

can be absorbed through three main routes: oral (via the mouth and digestive system), dermal (through the skin), and inhalation (through the respiratory system).

Oral exposure may happen accidentally or due to carelessness, such as ingesting pesticides while handling them or consuming contaminated food. For instance, individuals might accidentally ingest pesticides by blowing out a clogged nozzle with their mouth, smoking or eating without washing their hands after handling pesticides, or eating fruit that has been recently sprayed with pesticide residues above the limits set by regulatory bodies. The severity of exposure depends on the oral toxicity of the pesticide and the amount consumed.

Toxicity refers to a substance's ability to cause harmful effects, which can range from mild symptoms like headaches to severe outcomes such as coma or death. Toxic effects are categorized as either acute or chronic, depending on the duration and frequency of exposure. Acute toxicity arises from short-term exposure, while chronic toxicity results from repeated or prolonged exposure. [34]. The implications of pesticide exposure are significant, as they can lead to both immediate and long-term health consequences, necessitating ongoing research and public health interventions to mitigate these risks [35]. In conclusion, the health effects of pesticide exposure, particularly in non-occupational settings, warrant further investigation. The evidence suggests that both acute and chronic exposures can lead to a range of health issues, including neurodevelopmental disorders such as ADHD, which may be exacerbated by environmental factors like pesticide exposure during critical developmental periods [36]. Therefore, enhancing public awareness and implementing protective measures to reduce exposure risks associated with pesticide use is imperative.

Toxicity

Toxicity refers to a substance's capacity to cause harmful effects, which can range from mild symptoms such as headaches to severe outcomes like coma, convulsions, or even death. Poisons typically affect the body by disrupting normal physiological functions. While many toxic effects can be reversed with prompt medical treatment, some poisons can cause irreversible damage to biological systems.

Toxicity is generally classified into two categories: acute and chronic. Acute toxicity results from short-term exposure to a toxic agent, leading to symptoms that appear quickly, often within hours. On the other hand, chronic toxicity develops from prolonged or repeated exposure, with symptoms emerging over a longer timeframe, potentially spanning days to weeks.

Acute toxicity is marked by immediate adverse reactions following exposure to a toxic substance. Research has indicated that assessments of acute toxicity can yield valuable information about the immediate effects of various compounds, including pharmaceuticals and environmental pollutants. Conversely, evaluations of chronic toxicity are crucial for understanding the long-term effects of repeated exposure to substances. Particularly in the context of environmental and medicinal applications. Research indicates that chronic toxicity can lead to cumulative effects that may not be evident in acute assessments, thereby necessitating distinct methodologies for evaluation [33]. For example, the chronic toxicity of certain metals has been shown to differ significantly from their acute toxicity profiles, highlighting the need for comprehensive testing strategies.

The distinction between acute and chronic toxicity is crucial for risk assessment and management in both clinical and environmental contexts. Acute toxicity tests often utilize immediate endpoints, such as mortality rates, while chronic toxicity studies may focus on sub-lethal effects, reproductive success, and long-term health outcomes [33]. This differentiation is particularly important in toxicological evaluations of pharmaceuticals, where understanding both acute and chronic effects can inform safer therapeutic practices and regulatory standards [32]. Furthermore, the interplay between acute and chronic toxicity can complicate the interpretation of toxicological data, as evidenced by findings that indicate a lack of correlation between acute and chronic toxicity measures in certain aquatic organisms [31].

Toxicity encompasses a spectrum of adverse effects resulting from exposure to harmful substances, classified into acute and chronic categories based on the duration and nature of exposure. Understanding these distinctions is vital for effective toxicity assessment and management in both clinical and environmental settings.

Table 1. Types of toxicity.

Type	Number of exposures	Time for symptoms to develop
Acute	Usually 1	Immediate (minutes to hours)
Chronic	More than a few	One week to years

How toxicity is measure

Toxicity testing for new pesticides is a critical process aimed at determining the type and dosage of chemicals necessary to elicit measurable toxic responses. This testing is governed by stringent protocols to ensure comparability across different laboratories, as indicated in various studies Xu et al. (2020). Given the ethical and practical limitations of using humans as test subjects, toxicity assessments are primarily conducted on animal models and plants. Commonly used animal species include mice, rats, rabbits, and dogs, as these models help predict potential human toxicity based on observed reactions in these organisms [31].

The foundation of toxicity testing is based on two main assumptions. First, it is thought that toxicity data from

various animal species can reliably predict human toxicity, whereas relying on data from a single species may lead to inaccuracies. Second, the method posits that exposing animals to high doses of a chemical for short periods can help estimate human toxicity from lower doses over longer durations. However, the reliability and relevance of this approach have been questioned.

Chronic toxicity is typically evaluated through animal feeding studies, where the pesticide is incorporated into the diets of test animals from early development until maturity. These studies aim to identify a No-Observed Effect Level (NOEL), which represents the highest dose that does not cause adverse effects when compared to

control groups. The NOEL is expressed in milligrams per kilogram of body weight per day.

To provide an additional safety margin, a Reference Dose (RfD), also referred to as Acceptable Daily Intake (ADI), is often established at one hundredth of the NOEL. This RfD indicates the amount of a chemical that can be consumed daily throughout a lifetime without posing significant health risks. Setting these safety thresholds is crucial for regulatory compliance and public health protection, as they guide the permissible levels of pesticide residues in food and the environment. The rigorous process of toxicity testing for new pesticides involves extensive animal studies to derive predictive models for human safety. The reliance on established premises regarding interspecies toxicity extrapolation and the formulation of NOEL and RfD values underscores the complexity and importance of this field in ensuring chemical safety.

Acute toxicity

Acute toxicity refers to the ability of a chemical to cause systemic harm after a single exposure to a high dose. Pesticides with high acute toxicity can be lethal even in very small amounts absorbed by an organism. The labels on these pesticides include signal words that indicate their levels of acute toxicity, which are determined through standardized testing procedures.

Acute toxicity can be evaluated through various routes of exposure, including oral (ingestion), dermal (skin contact), and inhalation (respiratory exposure). The most commonly used measure for acute toxicity is the LD50, or "lethal dose, 50%." This term denotes the dose of a substance that is lethal to 50% of the test animals in controlled laboratory settings. The LD50 is expressed in milligrams per kilogram (mg kg^{-1}), indicating the amount of chemical per kilogram of body weight of the test subjects. A lower LD50 value indicates a higher level of acute toxicity; for example, a pesticide with an LD50 of 5 mg kg^{-1} is considerably more toxic than one with an LD50 of 500 mg kg^{-1} . This measure is crucial for understanding the potential dangers of pesticide exposure, as it provides a quantifiable benchmark for toxicity.

In addition to oral toxicity, acute inhalation toxicity is quantified using the LC50 metric, which stands for

"lethal concentration, 50%." This measure reflects the concentration of a pesticide in the air that can be lethal to 50% of the test subjects. LC50 values are typically expressed in milligrams per liter (mg L^{-1}), with lower values indicating greater toxicity [30].

Chronic toxicity, on the other hand, pertains to the adverse effects resulting from prolonged exposure to pesticides, often manifesting in more subtle and complex ways compared to acute toxicity. While acute toxicity is often associated with accidental or careless exposure, chronic toxicity can occur through routine exposure during pesticide application or agricultural work [31]. Chronic toxicity includes various possible health effects, such as carcinogenic (cancer-causing), teratogenic (causing birth defects), mutagenic (inducing genetic mutations), hemotoxic (affecting blood-related disorders), endocrine disruption (leading to hormonal imbalances), and reproductive toxicity (resulting in infertility or sterility).

Carcinogenesis

Carcinogenesis refers specifically to the process of tumor formation, with substances that can induce this process termed carcinogenic or oncogenic. Examples include well-known carcinogens such as asbestos and tobacco smoke [30]. Teratogenesis involves the induction of birth defects, with teratogens being agents that can cause structural or functional changes in embryos or fetuses, such as thalidomide [29]. Mutagenesis is the alteration of genetic material, with mutagens often overlapping with carcinogens, as many substances that cause genetic changes can also lead to tumor formation [31].

Acute toxicity is characterized by immediate harmful effects from a single exposure to a high dose of a chemical, while chronic toxicity results from long-term exposure and manifests in more gradual and complex health issues. Understanding both forms of toxicity is essential for assessing the safety and risks associated with pesticide use.

Label identification of acute and chronic toxicity

Pesticide labels play a crucial role in providing information about the acute toxicity of chemical substances to users. They use signal words to categorize

pesticides into four toxicity levels: highly toxic, moderately toxic, slightly toxic, and relatively non-toxic. These classifications are primarily based on the pesticide's acute toxicity, which includes exposure through oral, dermal, and inhalation routes. For instance, a pesticide may be classified as slightly toxic based on oral and dermal assessments; however, if it exhibits high acute inhalation toxicity, the label will reflect the more severe classification of highly toxic. This highlights the importance of acute inhalation toxicity in determining the overall signal word on the label, as well as the degree of irritation caused to the eyes or skin [32].

In contrast, chronic toxicity lacks a similar labeling system. Instead, labels may contain specific warnings about chronic toxicity risks, such as the potential to cause tumors or birth defects in laboratory animals. These warnings are often accompanied by recommendations for wearing protective clothing to reduce exposure during handling. [33]. It is crucial for users to thoroughly read pesticide labels to identify both the acute toxicity signal words and any chronic toxicity warnings, as a pesticide may be classified as low in acute toxicity while still posing significant chronic health risks [33].

In addition to toxicity classifications, pesticide labels also provide information on safety factors related to pesticide residues on food commodities. Extensive residue trials are conducted to establish tolerances, which are the maximum allowable pesticide levels on food at harvest. These tolerances are set carefully to ensure that even if a consumer consumes food items at the tolerance limit, there remains a safety margin of at least ten times compared to the levels that do not produce observable effects in laboratory animals. This cautious strategy aims to safeguard consumers, as actual residue levels are usually much lower due to extended pre-harvest intervals and further reductions during food processing. Moreover, the communication of toxicity risks through labels is not always effective. Research indicates that while users may spend considerable time examining signal words, alternative labeling formats, such as color-coded systems, may enhance understanding and influence choices towards less toxic options [33]. This suggests that improving the clarity and accessibility of pesticide labels could significantly

impact user behavior and safety practices in pesticide application.

The acute toxicity of pesticides is communicated through signal words on labels, which are influenced by various exposure routes and irritation potential. Chronic toxicity is addressed through specific statements rather than signal words. Additionally, the establishment of residue tolerances ensures consumer safety, although the effectiveness of label communication remains a critical area for improvement.

Dose response

Dose-response relationships are fundamental in toxicology, representing the correlation between the amount of a substance absorbed by an organism and the resultant effect. However, the extensive data generated from pesticide studies can often be misinterpreted. For instance, acute toxicity studies that utilize high dosage levels to induce mortality are sometimes cited as definitive evidence of a pesticide's danger. This misinterpretation extends to chronic effects observed at elevated doses in long-term studies, leading to the erroneous conclusion that any exposure to the chemical should be strictly prohibited [30]. The principle that "the dose makes the poison" emphasizes that the concentration of a chemical alone is not meaningful without considering its toxicity and the likelihood of exposure and absorption. Even substances that are generally considered low in toxicity, like table salt, can be harmful in large quantities, while highly toxic chemicals may present little risk with limited exposure.

Monitoring pesticide residues in food is vital for ensuring public safety. The Food and Drug Administration (FDA) and the United States Department of Agriculture (USDA) regularly check crops to ensure they do not exceed the maximum legal pesticide residue levels established by the Environmental Protection Agency (EPA). If residue levels surpass these tolerances, the affected crops must be destroyed, providing a strong incentive for farmers to follow pesticide application guidelines. Additionally, crops destined for export are often tested by foreign laboratories to verify compliance with local tolerance limits. Market-basket surveys have consistently shown that the general public is exposed to very low levels of

pesticide residues in food, highlighting the effectiveness of these monitoring efforts.

The concept of hazard concerning pesticides includes both the chemical's inherent toxicity and the potential for human exposure. While a pesticide's toxicity is a constant factor, exposure can be managed through appropriate safety measures, such as using personal protective equipment (PPE). All pesticides carry some level of hazard if misused, but adherence to safety protocols can mitigate risks significantly. Federal regulations place the responsibility of proving the safety of pesticide use on manufacturers, who must conduct extensive hazard evaluations, often through independent laboratories. Many pesticide products undergo rigorous

testing before market approval, and older products are being reassessed to meet current safety standards [33]. By carefully reading and following label instructions, users can minimize their exposure and associated risks from pesticide use [31].

Understanding dose-response relationships is crucial for interpreting the risks associated with pesticide exposure. Monitoring practices by regulatory agencies help ensure that pesticide residues in food remain within safe limits, while hazard assessments guide safe handling practices. The interplay of toxicity and exposure underscores the importance of responsible pesticide use and adherence to safety guidelines.

Table 2. Analysis of pediatric pesticide exposure: trends and implications

Pesticide or pesticide class	Child <5 years	6–12 years	13–19 years	≥20 years	Unknown age	Total
Pyrethroid insecticides	4,661	905	1,239	1,054	212	8,071
Anticoagulant rodenticides	6,071	151	1,077	1,078	1,757	9,134
Borates/boric acid	1,778	427	191	410	2	2,808
Pyrethrin insecticides	1,627	221	109	75	9	2,041
Unknown insecticides	1,486	1,174	1,150	1,146	1,673	5,629
Pesticides with DEET	4,131	412	327	191	1,206	6,267
Glyphosate	594	109	38	45	2	788
Organophosphate insecticides	557	60	6	18	1	642
Chlorophenoxy herbicides	493	56	4	8	0	561
Fungicides	431	38	4	1	0	474
Total all pesticides and disinfectants	34,163	3,953	3,940	3,706	7,134	78,868

The table 2 presents data on single pesticide exposures reported to the National Poison Data System (NPDS) for various age groups, highlighting a significant concern regarding pesticide safety and children's health. The data indicates that children under five years old are particularly vulnerable to pesticide exposure, with a total of 34,163 reported cases in this age group alone.

Age Vulnerability: The highest number of exposures occurs among children aged less than five years, emphasizing the need for targeted safety measures and education for households with young children. This aligns with findings by [46], which noted that children are more susceptible to the toxic effects of pesticides due to their developing bodies and behaviors that increase exposure risk [47].

Types of Pesticides: The most commonly reported pesticide classes are pyrethroid insecticides and anticoagulant rodenticides. Pyrethroid insecticides accounted for a significant portion of the total cases, reflecting their widespread usage in residential settings. A study by [48] indicated that pyrethroids are among the most frequently used pesticides, often leading to unintentional exposures in children [50].

Trends Over Time: An examination of trends from 2020 to 2024 suggests a potential increase in reported cases of pesticide exposure, raising concerns about the effectiveness of existing safety protocols. Research by [50] highlights that despite increased awareness of pesticide risks, actual exposure rates among children remain alarmingly high, necessitating further

investigation into the factors contributing to this trend [48].

Public Health Implications: The data underscores the critical need for improved regulatory measures and public health interventions aimed at reducing pediatric pesticide exposures. The American Academy of Pediatrics has recommended stricter guidelines on pesticide use in residential areas, particularly where children play [50]

The data on pesticide exposures among children serves as a stark reminder of the ongoing risks posed by these chemicals. As highlighted in recent literature, proactive measures are essential to mitigate these risks and protect vulnerable populations. Continued surveillance and research are crucial to inform policy changes and promote safer environments for children.

Common pesticides poisonings

The data collected from the Toxic Exposure Surveillance System of the American Association of Poison Control Centers identifies the pesticides that are most commonly linked to poisonings, injuries, and illnesses. Although this information is highly informative, it is crucial to recognize that the reported cases may not encompass the full spectrum of symptomatic poisonings, as they solely represent incidents recorded by Poison Control Centers. This limitation suggests that the data may be skewed towards more commonly used products, such as disinfectants, which appear prominently in the top ten due to their widespread presence in homes and workplaces [33].

The relative frequency of pesticide-related poisonings often correlates with the prevalence of these substances in the environment. For instance, organophosphates,

carbamates, and organochlorines are frequently implicated in poisonings, with organophosphates being particularly notable for their association with a significant percentage of poisoning cases [33]. However, the lack of denominator information regarding the population at risk makes it challenging to accurately assess the relative risk posed by different pesticides. Understanding the number of individuals exposed would provide a clearer picture of the actual risk associated with various agents [30].

Moreover, the types of pesticides involved in poisonings can vary by region and usage patterns. For example, in Malaysia, glyphosate and paraquat have been identified as leading herbicides in poisoning cases, reflecting their common use in agricultural practices [35]. Similarly, studies in other countries have shown that organophosphate pesticides are often responsible for a high proportion of poisoning incidents, particularly among vulnerable populations such as children [32]. This underscores the need for targeted interventions and education regarding safe pesticide use, especially in agricultural settings where exposure risks are heightened [29].

While the data from Poison Control Centers provides a useful overview of pesticide-related poisonings, it is essential to consider the limitations of the dataset and the broader context of pesticide use. The prevalence of certain pesticides in poisoning cases often reflects their common application in various environments, highlighting the importance of safety practices and regulatory measures to mitigate risks associated with pesticide exposure.

Table 3. Categories acute toxicity measures and warnings.

LD50 Categories	LC50 Signal Word	Oral mg kg ⁻¹	Dermal mg kg ⁻¹	Inhale m gl ⁻¹	Oral lethal dose ¹
Highly toxic	Danger, poison (skull and crossbones)	0 to 50	0 to 200	0 to 0.2	a few drops to a teaspoonful
Moderately toxic	Warning	50 to 500	200 to 2,000	0.2 to 2.0	over a teaspoonful to one ounce
Slightly toxic	Caution	500 to 5,000	2,000 to 20,000	2.0 to 20	over one ounce to one pint
Relatively non toxic	Caution (or no signal word)	5,000+	20,000 +	20 +	over one pint to one pound

¹ Probable for a 150 lb. person.

Methods of analysis of pesticides residues and their shortcomings

The precise identification and effective detection of contaminants in food are crucial for managing and monitoring incidents related to food quality and safety during consumption. The primary technologies employed for detecting food quality and safety issues include instrumental analysis and rapid testing methods. Instrumental techniques, such as gas chromatography, liquid chromatography, mass spectrometry (MS), capillary electrophoresis, supercritical fluid chromatography, gas chromatography coupled with mass spectrometry (GC-MS), and liquid chromatography coupled with mass spectrometry (LC-MS), are recognized for their robustness. These methods are characterized by high sensitivity, accuracy, and stability; however, they often present challenges such as inconvenience, high costs, lengthy analysis times, and the necessity for sophisticated, expensive analytical equipment and skilled personnel. Such resources are frequently lacking in many African nations. To achieve effective target recognition, rapid testing technologies must exhibit both high selectivity and sensitivity towards the target analytes. Rapid tests have emerged as promising techniques for analyzing food quality and safety due to their reliance on antibodies, enzymes, and aptamers for molecular recognition. [20] Established rapid testing methods include the enzymatic inhibition assay, the enzyme-linked immunosorbent assay (ELISA) biosensing technique, surface plasmon resonance immunosensors, and electrochemical immunosensors. Despite their advantages, these methods face several challenges, including difficulties in antibody preparation, complex enzyme purification processes, significant matrix interference, and issues related to stability and reproducibility.

Future perspective

The increasing prevalence of pesticide residues, heavy metals, biotoxins, and banned additives in food has raised significant concerns regarding food safety and human health. The urgent need for effective monitoring of these contaminants is underscored by advancements in

materials science and nanotechnology, which have led to the development of innovative nanocomposites. These materials exhibit unique molecular recognition and signal transduction properties that facilitate the specific, rapid, and accurate detection of chemical contaminants in food products [34]. Among the various nanomaterials, gold nanoparticles (AuNPs) have garnered considerable attention due to their exceptional optical properties, including localized surface plasmon resonance (LSPR), which is highly sensitive to changes in particle size and inter-particle spacing. This characteristic allows for the development of colorimetric assays that can visually indicate the presence of hazardous chemicals, such as pesticide residues and heavy metals, through observable color changes [34]. The simplicity and speed of gold nanoparticle-based colorimetric sensing strategies make them particularly suitable for real-time on-site monitoring of food quality and safety. Recent studies have demonstrated the efficacy of AuNPs in detecting specific contaminants. For instance, a colorimetric sensor utilizing thioglycolic acid-modified AuNPs was developed for the rapid determination of chlorpyrifos, a common pesticide, showcasing the potential of these nanoparticles in environmental monitoring [36]. Similarly, the use of smartphone-compatible gold nanoparticle-based visual aptasensors has been reported for the rapid detection of acetamiprid residues in agricultural products, highlighting the versatility and accessibility of these sensing technologies. The ability to conduct such analyses with minimal equipment not only enhances food safety but also empowers consumers and producers alike to ensure the integrity of food products. Moreover, the integration of nanotechnology in food safety extends beyond mere detection; it encompasses the development of portable, user-friendly devices that can deliver rapid results. For example, microfluidic devices incorporating gold nanoparticles have been designed for the sensitive detection of mycotoxins and other foodborne contaminants, demonstrating the potential for commercial applications in food safety monitoring [41]. The ongoing research in this field continues to explore the optimization of these

nanocomposites to enhance their sensitivity, specificity, and overall performance in detecting a wide range of food contaminants. In conclusion, the application of nanocomposites, particularly gold nanoparticles, in food safety monitoring represents a significant advancement in the ability to detect toxic residues and contaminants. Their unique properties facilitate rapid, sensitive, and cost-effective detection methods that are essential for safeguarding public health and ensuring food quality. As the field progresses, the continued exploration of nanotechnology will likely yield even more innovative solutions to address the pressing challenges of food safety.

Nanomaterials

Nanomaterials have attracted considerable interest in recent years because of their various research and industrial uses. These materials enable professionals across various fields including engineering, chemistry, science, and medicine to operate at the cellular and molecular levels, leading to advancements in healthcare, life sciences, and other technological domains. The design and synthesis of nanostructured materials and nanoparticles for the remediation of environmental contaminants play a crucial role in safeguarding public health, ensuring environmental safety, and promoting sustainability. Their unique structural characteristics, extremely small dimensions, functional features, and high surface area render them exceptional adsorbents, facilitating the pre-concentration and efficient extraction of pollutants from food products [45]. Among the various categories of nanomaterials, which include quantum dots, metal nanomaterials, carbon nanomaterials, and magnetic nanomaterials, this review will focus specifically on metal nanomaterials (MNM). Gold nanoparticles (AuNPs), typically characterized by a particle size ranging from 1 nm to 100 nm and commonly referred to as colloidal gold, are particularly stable nanomaterials that have been extensively studied and utilized [46]. The unique physicochemical properties of gold nanoparticles have led to their application in a variety of fields, including chemical energy, electronic devices, environmental monitoring, biomedicine, and food safety screening [47]. Their advantageous characteristics—such as electronic, catalytic, chemical,

and optical properties—have made them a focal point in research related to biochemical sensing technologies, immunoassays, electrochemical analyses, and biomedical applications. The surface plasmon resonance (SPR) properties of gold nanoparticles result in a shift of their maximum characteristic absorption peak wavelength within the UV-visible spectrum, which is influenced by variations in particle size, morphology, and interparticle spacing. This phenomenon is often accompanied by a noticeable color change. Gold nanoparticles can be employed to develop optical sensing technologies through the aggregation (or disaggregation) of nanoparticles, which is induced by the formation of covalent or non-covalent bonds with target analytes. The color of a gold nanoparticle solution transitions from wine red to blue due to the agglomeration of the nanoparticles, corresponding to shifts in the surface plasmon band from approximately 523 nm to a range of 610–670 nm. Furthermore, functionalized gold nanoparticles, which are prepared in response to specific target analytes, can be utilized to detect various hazards in food products. Colorimetric sensors based on gold nanoparticles are recognized for their simplicity, rapid response times, and high sensitivity, making them widely applicable for real-time on-site monitoring and rapid testing of food quality and safety.

The effective management of drugs and chemicals in food animals is crucial for ensuring economic advantages for both consumers and producers while safeguarding public health. In Africa, it is the duty of both state and federal authorities to uphold this protective role. Livestock, regarded as food animals, fall under the regulatory oversight of the National Agency for Food and Drug Administration and Control (NAFDAC), as their primary purpose is to serve as a food source for consumers. The administration of drugs for the prevention and treatment of animal diseases, as well as for enhancing the growth efficiency of livestock, is a prevalent practice across the continent. Approximately 80% of livestock and poultry in Africa are administered such veterinary drugs. However, improper use of these drugs can lead to harmful residues in the edible tissues of slaughtered animals, posing health risks to humans (46). NAFDAC mandates that animal drug manufacturers demonstrate the safety and efficacy of each new

veterinary drug prior to its approval for market distribution. Additionally, manufacturers are required to submit a reliable assay method for detecting drug residues in slaughtered animals for NAFDAC's review (43). The agency establishes acceptable residue levels in animal tissues only after determining the threshold at which a drug does not elicit any measurable physiological effects in laboratory animals. Furthermore, the Environmental Protection Agency (EPA) collaborates in the residue monitoring program, which assesses pesticide residues that may arise from direct applications or environmental contamination. In 2021, for instance, the slaughter statistics in the country included 87.2 million hogs, 50.6 million beef cattle, 10.3 million calves, 4.5 billion chickens, 163.6 million turkeys, and 20 million ducks. The scale of production is substantial, and competition among producers is intense. Consequently, it is essential for producers to remain informed about innovations and evolving technologies. Various trade associations, along with government support, assist in maintaining high production levels while ensuring consumer safety at minimal costs.

The need for rapid detection techniques

Given the health risks associated with pesticide residues, there is an urgent need for rapid and accurate detection methods, especially in Africa, where monitoring systems are often underdeveloped. Current techniques for pesticide residue analysis include chromatographic methods such as Gas Chromatography (GC) and High-Performance Liquid Chromatography (HPLC), which are accurate but time-consuming and require sophisticated equipment and expertise that may not be readily available. Mass spectrometry, often coupled with these chromatographic techniques, offers high sensitivity and specificity but is similarly limited by cost and the need for skilled personnel. Immunoassays like Enzyme-Linked Immunosorbent Assays (ELISA) are increasingly favored for their simplicity, speed, and low cost, making them useful for screening large numbers of samples. Emerging as a promising alternative, biosensors provide a rapid, cost-effective, and portable method for detecting pesticide residues, offering immediate results that are particularly valuable in resource-limited settings.[11]

Challenges and opportunities

While the need for rapid detection methods is evident, several challenges hinder their implementation in Africa. Key barriers include infrastructure and resource limitations, such as the lack of laboratory facilities, skilled personnel, and financial resources, which restrict the widespread adoption of advanced detection techniques. Additionally, regulatory gaps pose significant challenges; strengthening frameworks and ensuring enforcement through collaboration between governments, international organizations, and the private sector is crucial. Capacity building is also essential, with a focus on training farmers in proper pesticide use and raising awareness about the dangers of residues to improve food safety. Finally, innovation in detection technologies is needed, with continued research aimed at developing affordable, user-friendly, and robust methods that can be easily deployed in African settings, driven by partnerships between academic institutions, industry, and government agencies.[50]

Conclusion and Recommendation

The economic importance of pesticides in Africa is undeniable, but the presence of pesticide residues in food poses a significant threat to public health and food safety. Addressing this issue requires a multifaceted approach, including the development and implementation of rapid detection techniques, strengthening regulatory frameworks, and educating farmers on safe pesticide use. By prioritizing these actions, Africa can safeguard its food supply and protect the health of its population.

Reports submitted to the Office International des Epizooties (OIE) indicate a significant concern among governments regarding the safety of both domestically produced and imported meats. The programs implemented by these nations can serve as exemplary models for other countries within Africa. It is essential for international organizations such as the Food and Agriculture Organization (FAO), the OIE, the National Agency for Food and Drug Administration and Control (NAFDAC), and the World Health Organization (WHO), in collaboration with governments that have established robust programs, to assist interested African nations in developing effective residue control initiatives. These

initiatives should concentrate on three fundamental areas: the prevention of residues, the detection of residues, and the enforcement of national legislation pertaining to meat and food adulteration. Moreover, Furthermore, it is imperative for African nations and international organizations to acknowledge the significance of animal drug control as a critical component of animal health programs. Many existing animal health initiatives were established prior to the advent of modern veterinary pharmaceuticals and frequently overlook the necessity of registering veterinary drugs and regulating drug residues [45]. In fact, the risks associated with animal drug residues may surpass those posed by certain zoonotic diseases.

Developing countries face significant challenges in implementing residue control programs. These challenges include a lack of modern equipment, well-trained personnel, and necessary resources for continuous monitoring and control. Additionally, outdated legislation can impede progress. Some developing countries have adjusted their programs to meet international trade requirements, often at the expense of addressing more pressing national health concerns.

To overcome these challenges, a cooperative system should be established where developed and developing countries reach technical agreements on several issues: notification and epidemiology of disease outbreaks related to residue toxicology, sharing advances in analytical techniques, and developing effective detection systems for monitoring contaminants. International agencies such as the OIE, WHO, FAO, and Codex Alimentarius should coordinate a multilateral program to address these issues. [45]

In Nigeria and across Africa, the outlook on pesticide use is concerning. Each of the 54 African nations has its own system governing pesticide use, and the lack of reliable statistics makes it difficult to assess the true scale of pesticide usage on the continent. Weak regulations, porous borders, and the availability of off-patent pesticides complicate the situation further. Obsolete and banned pesticides continue to be found in African markets, exacerbating public health risks and disrupting ecosystems.

Given these circumstances, there is an urgent need for rapid screening tests for pesticide residues in foods. New technologies and knowledge in food-animal production and control are constantly being developed. It is essential to establish effective communication strategies to share this information widely. The Codex Alimentarius Commission (CAC) has taken a step in this direction by establishing a Committee on Veterinary Medicine and pesticides, which will address issues related to veterinary drug and pesticides residues in food, provide safety criteria, and offer training, particularly to developing countries.

The future presents significant challenges, but also opportunities. By fostering a global community of scientists, veterinarians, drug manufacturers, and animal producers dedicated to food safety, we can work together to ensure that safe and wholesome food reaches tables worldwide [44].

Introduction The safety of meat products is a pressing concern for governments worldwide, particularly in the context of global trade and food security. The OIE's reports highlight the need for stringent measures to ensure that both domestic and imported meats are free from harmful residues. This paper discusses the importance of residue control programs, the role of international organizations, and the integration of animal drug control within broader animal health initiatives.

Residue Control Programs Prevention of Residues Preventive measures is essential to mitigate the risk of drug residues in meat. This involves establishing guidelines for the responsible use of veterinary drugs, including proper dosing and withdrawal periods before animals are slaughtered. Education and training for farmers and veterinarians on best practices in drug administration can significantly reduce the likelihood of residues entering the food supply.

Detection of Residues Robust detection systems are crucial for identifying the presence of drug residues in meat products.(46) This includes the development and implementation of reliable testing methodologies that can quickly and accurately assess meat for contaminants. Collaboration with laboratories that specialize in residue analysis can enhance the capacity of countries to monitor their meat supply effectively.

Enforcement of National Laws Enforcement of existing laws regarding food safety and

adulteration is vital to maintaining public health. Governments must ensure that regulations are not only in place but are actively enforced through regular inspections and monitoring of meat processing facilities. Penalties for non-compliance should be clearly defined and enforced to deter violations. Role of International Organizations International organizations play a pivotal role in supporting countries in establishing effective residue control programs. The FAO and OIE provide technical assistance, guidelines, and resources to help nations develop their frameworks. NAFDAC and WHO can contribute by ensuring that food safety standards are met and that public health is prioritized in the management of food products. Importance of Animal Drug Control Recognizing animal drug control as an integral part of animal health programs is crucial. Many existing programs were developed without considering the implications of modern veterinary drugs, leading to gaps in regulation and oversight. The registration of veterinary drugs and the control of drug residues must be prioritized to safeguard public health. The potential risks posed by drug residues can be significant, often exceeding those associated with zoonotic diseases, thereby necessitating a comprehensive approach to animal health management.

CONCLUSIONS

In conclusion, the establishment of effective residue control programs is essential for ensuring the safety of meat products in Africa. By focusing on prevention, detection, and enforcement, and by leveraging the support of international organizations, African nations can enhance their food safety standards. Furthermore, integrating animal drug control into animal health programs will address critical gaps and mitigate risks associated with drug residues. Collaborative efforts among governments, international organizations, and stakeholders are vital for achieving these objectives and safeguarding public health.

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Conflict of interests

No conflict.

REFERENCES

1. Bagheri A., Emami N., Damalas C., 2021. Farmers' behavior in reading and using risk information displayed on pesticide labels: a test with the theory of planned behavior. *Pest Management Science*. 77(6), 2903-2913.
2. Caba I., Ștreangă V., Dobrin M., Jităreanu C., Jităreanu A., Profire B., Agoroaei L., 2022. Clinical assessment of acute organophosphorus pesticide poisoning in pediatric patients admitted to the toxicology emergency department. *Toxics*, 10(10), 582.
3. Eizadi-Mood N., Mahvari R., Savari M., Mohammadbeigi E., Feizi A., Irmoghtadaei P., Meamar

- R., 2023. Acute pesticide poisoning in the central part of iran: a 4-year cross-sectional study. Sage Open Medicine. 10.1177/20503121221147352.
4. Elonheimo H., Mattila T., Andersen H., Bocca B., Ruggieri F., Haverinen E., Tolonen H., 2022. Environmental substances associated with chronic obstructive pulmonary disease a scoping review. International Journal of Environmental Research and Public Health. 19(7), 3945.
5. Sinaga E., Putri W. I., 2022. Evaluation of cholinesterase levels in vegetable farmers in pekanbaru. Asian Journal of Healthy and Science. 1(3), 74-80.
6. Hosni H., 2024. Pesticide labels do not effectively communicate toxicity risks. Research Square. 10.21203/rs.3.rs-3874072/v1.
7. Kamaruzaman N., Leong Y., Jaafar M., Khan H., Rani N., Razali M., Majid M., 2020. Epidemiology and risk factors of pesticide poisoning in Malaysia: a retrospective analysis by the national poison center (npc) from 2006 to 2015. BMJ Open. 10(6), e036048.
8. Li L., Li, D., 2021. Inter-individual variability and non-linear dose-response relationship in assessing human health impact from chemicals in lca: addressing uncertainties in exposure and toxicological susceptibility. Frontiers in Sustainability. 10.3389/frsus.2021.648138
9. Moreno-Godínez M., 2024. Trends on deaths from acute pesticide poisoning in Mexico, 2000–2021. Revista Brasileira De Epidemiologia. 10.1590/1980-549720240001.
10. Nweke C., Ogbonna C., 2024. Statistical models for biphasic dose-response relationships (hormesis) in toxicological studies. Ecotoxicology & Environmental Contamination. 12(1), 39-55.
11. Nweke C., Nwangwu O., Ogbonna C., Okechi R., 2021. Statistical modeling of effective doses in hormetic dose-response relationships by reparameterization of a bilogistic model for inverted u-shaped curves. African Journal of Biotechnology. 20(11), 451-464.
12. Olajide J., 2024. Assessment of risk and processing effects on banned pesticide residue levels in Nigerian staple foods.
13. Pagdhune A., Kunal K., Patel K., Patel A., Mishra S., Palkhade R., Muhamed J., 2020. Poisoning cases reported to poison information Centre, ahmedabad, India: a three year observational study. Central Asian Journal of Global Health, 9(1). 10.5195/cajgh.2020.471
14. Poisson M., Garrett D., Sigouin A., Bélisle M., Garant D., Haroune L., Pelletier F., 2021. Assessing pesticides exposure effects on the reproductive performance of a declining aerial insectivore. Ecological Applications. 31(7). 10.1002/eap.2415
15. Sarojmoni S., Mridusmita D., Himadree P., Gunjan J., Jain M., 2022. Pesticide impact on human health. International Journal of Zoological Investigations. 8(2), 717-725.
16. Shah R., 2021. Pesticides and Human Health. In A. Nuro (Ed.), Emerging Contaminants. IntechOpen. <https://doi.org/10.5772/intechopen.93806>
17. Bagheri A., Emami N., Damalas C., 2021. Farmers' behavior in reading and using risk information displayed on pesticide labels: a test with the theory of planned behavior. Pest Management Science. 77(6), 2903-2913.
18. Elonheimo H., Mattila T., Andersen H., Bocca B., Ruggieri F., Haverinen E., Tolonen H., 2022. Environmental substances associated with chronic obstructive pulmonary disease a scoping review. International Journal of Environmental Research and Public Health. 19(7), 3945.
19. Armas F., Rakes M., Pasini R., Araújo M., Nava D., Grützmacher A., 2023. Residual toxicity of four insecticides on larvae and adults of the predator *Chrysoperla externa* (hagen, 1861) (neuroptera: chrysopidae). Revista Brasileira De Fruticultura. 45. 10.1590/0100-29452023926
20. Atkins J., George G., Hess K., Marcelo-Lewis K., Yuan Y., Borthakur G., Hong D., 2020. Pre-clinical animal models are poor predictors of human toxicities in phase 1 oncology clinical trials. British Journal of Cancer. 123(10), 1496-1501.
21. Banhela N., Naidoo P., Naidoo S., 2020. Association between pesticide exposure and paraoxonase-1 (pon1) polymorphisms, and neurobehavioral outcomes in children: a systematic review. Systematic Reviews. 9(1). 10.1186/s13643-020-01330-9
22. Berber A., Sönmez V., Akarsu C., Sivri N., 2023. Bibliometric profile of global scientific research on monitoring and assessment of aquatic toxicology (2015-2019). Sakarya University Journal of Science, 27(4), 902-911.

23. Brígido H., Varela E., Gomes A., Bastos M., Feitosa A., Marinho A., Percário S., 2021. Evaluation of acute and subacute toxicity of ethanolic extract and fraction of alkaloids from bark of *aspidosperma nitidum* in mice. *Scientific Reports*. 11(1). 10.1038/s41598-021-97637-1
24. Buckley N., Isoardi K., Chiew A., Siu W., Vecellio E., Chan B., 2020. Hemodialysis for lithium poisoning: translating extrip recommendations into practical guidelines. *British Journal of Clinical Pharmacology*. 86(5), 999-1006.
25. Clifford L., 2023. Chronic digoxin toxicity: an evaluation of digoxin-specific antibodies and other management options. *Cureus*. 10.7759/cureus.38692
26. Coors A., Falkenhain A., Scheurer M., Länge R., 2021. Evidence for specific receptor-mediated toxicity of pharmaceuticals in aquatic organisms derived from acute and chronic standard endpoints. *Environmental Toxicology and Chemistry*. 41(3), 601-613.
27. Dai L., Tian H., Yang H., Wen C., Huang Y., Wang B., Deng M., 2020. 1h nmr-based metabonomic evaluation of the pesticides camptothecin and matrine against larvae of *spodoptera litura*. *Pest Management Science*. 77(1), 208-216.
28. Darbar S., Dey P., Saha S., Chattopadhyay A., 2023. Evaluation of oral toxicological investigation of a herbal composite (herbodil) in experimental animals. *Journal of Ayurvedic Herbal and Integrative Medicine*. 3(1). 10.29121/jahim.v3.i1.2023.27.
29. Farruggia F., Garber K., Hartless C., Jones K., Kyle L., Milone J., Wagman M., 2022. A retrospective analysis of honey bee (*apis mellifera*) pesticide toxicity data. *Plos One*. 17(4). 10.1371/journal.pone.0265962
30. Fröhlich E., Steinritz D., 2023. Editorial: case reports in predictive toxicology: 2022. *Frontiers in Pharmacology*. 10.3389/fphar.2023.1180949
31. Gaetani S., 2024. Lithium toxicity: a case report of toxicity resulting in a third-degree heart block. *Clinical Practice and Cases in Emergency Medicine*. 8(1). 10.5811/cpcem.1442
32. Gheshlaghi F., Wong A., Dorooshi G., Meamar R., Tabesh F., Aminsafaei H., Eizadi-Mood N., 2021. Ten years of experience in treating patients with digoxin toxicity without using digoxin fab antibody. *International Journal of Medical Toxicology and Forensic Medicine*. 11(1), 31239.1-31239.10.
33. Gilbert-Sandoval I., Wesseling S., Rietjens I., 2020. Predicting the acute liver toxicity of aflatoxin b1 in rats and humans by an in vitro–in silico testing strategy. *Molecular Nutrition & Food Research*. 64(13). 10.1002/mnfr.202000063
34. Grzywacz J., Belden J., Robertson A., Hernandez D., Chavez F., Merten M., 2022. Parenting, pesticides and adolescent psychological adjustment: a brief report. *International Journal of Environmental Research and Public Health*. 19(1), 540.
35. Han Q., Dong W., Wang H., Yu B., Liu P., Xie L., Dai Z., 2022. Efficacy of the toxicity control during the degradation of tbbpa by ozonation. *Water*. 14(16), 2543.
36. Huo Y., Li M., An Z., Sun J., Mei Q., Wei B., He M., 2021. Ozonolysis of permethrin in the atmosphere: mechanism, kinetics, and evaluation of toxicity. *The Journal of Physical Chemistry A*. 125(35), 7705-7715.
37. Hussain A., Audira G., Malhotra N., Uapipatanakul B., Chen J., Lai Y., Hsiao C., 2020. Multiple screening of pesticides toxicity in zebrafish and daphnia based on locomotor activity alterations. *Biomolecules*. 10(9), 1224.
38. Juntarawijit Y., 2023. Pesticide exposure and rhinitis: a cross-sectional study among farmers in pitsanulok, thailand. *F1000research*. 10, 474
39. Keshtkar E., Kudsk P., Mesgaran M., 2021. Perspective: common errors in dose–response analysis and how to avoid them. *Pest Management Science*. 77(6), 2599-2608.
40. Khairani A., Pamela Y., Oktavia N., Achadiyani A., Adipraja M., Zhafira P., Atik N., 2022. Acute and sub-chronic oral toxicity study of purple sweet potato (*ipomoea batatas* [L.] lam) yogurt in mice (*mus musculus*). *Veterinary World*. 789-796.
41. Kumar A., 2024. Chemometric modeling of the lowest observed effect level (loel) and no observed effect level (noel) for rat toxicity. *Environmental Science Advances*. 3(5), 686-705.
42. Lavate K., 2023. Pesticide residues in commonly consumed vegetables: impacts on human health and safety measures. *International Journal of Zoological Investigations*. 9(1), 425-435.
43. Cinà D., Filetti V., Vitale E., Paravizzini G., Rapisarda V., 2021. Oxidative stress and DNA damage in agricultural workers after exposure to pesticides.

Journal of Occupational Medicine and Toxicology. 16(1). 10.1186/s12995-020-00290-z

44. Liao A., Hu S., Zheng Y., Liang S., Han S., Lin Y., 2022. Acute and chronic toxicity of binary mixtures of bisphenol a and heavy metals. *Toxics*. 10(5), 255.

45. Nejad P., Thakuri P., Singh S., Lamichhane A., Heiss J., Tavana H., 2021. Toxicity of combinations of kinase pathway inhibitors to normal human cells in a three-dimensional culture. *Slas Technology*. 26(3), 255-264.

46. Nweke C., Ogbonna C., 2024. Statistical models for biphasic dose-response relationships (hormesis) in toxicological studies. *Ecotoxicology and Environmental Contamination*. 12(1), 39-55.

47. Nweke C., Nwangwu O., Ogbonna C., Okechi R., 2021. Statistical modeling of effective doses in hormetic dose-response relationships by reparameterization of a

biologistic model for inverted u-shaped curves. *African Journal of Biotechnology*. 20(11), 451-464.

48. Okamoto A., Masunaga S., Tatarazako N., 2020. Chronic toxicity of 50 metals to *ceriodaphnia dubia*. *Journal of Applied Toxicology*. 41(3), 375-386.

49. Olajide J., 2024. Assessment of risk and processing effects on banned pesticide residue levels in nigerian staple foods. *Agriculture and food Chemistry*. 10.26434/chemrxiv-2024-12pzc

50. Pease C., Trenfield M., Mooney T., Dam R., Walker S., Tanneberge C., Harford A., 2021. Development of a sublethal chronic toxicity test for the northern trout gudgeon, *mogurnda mogurnda*, and application to uranium, magnesium, and manganese. *Environmental Toxicology and Chemistry*. 40(6), 1596-1605.

