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A Comprehensive Review On Pesticides: Classifications, Sources, Impacts, And Analytical Methods

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Abstract

Background: *Pesticides are synthetic compounds that are widely used to control pests, insects, and weeds in various settings. They are classified into organophosphates, carbamates, pyrethroids, neonicotinoids, and organochlorines, based on their chemical structure and mode of action. Although pesticides have significantly contributed to increased agricultural productivity, their widespread use has raised concerns regarding environmental contamination and potential health risks. Pesticides originate from various sources including agricultural runoff, industrial discharge, urban pest control, wastewater treatment plants, and landfill leachates. They have significant negative environmental effects such as contamination of surface water and groundwater, bioaccumulation in aquatic organisms, disruption of non-target species, and soil degradation. Pesticide exposure also poses risks to human health, including acute and chronic toxicity, leading to carcinogenicity, endocrine disruption, and reproductive toxicity.*

Conclusion: *The presence of pesticide residues in food and drinking water is a serious public health concern. To address these issues, sensitive and selective analytical methods have been developed for pesticide detection, including spectroscopic (UV-Vis and FT-IR), chromatographic (TLC, HPLC, GC-ECD, and GC-MS), electrochemical (DPV), and bioanalytical techniques (ELISA and biosensors). This study provides a comprehensive review of the* ***c****lassification, sources, impacts, and analytical methods of pesticides analysis****.***

Key word: *Pesticides, Classifications, Sources, Impacts, and Analytical Methods.*

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I. Introduction

Pesticides are synthetic compounds that are used to control pests, insects, and weeds in agricultural and domestic settings. They are classified into several groups based on their chemical structures and modes of action (Mdeni et al., 2022). Organophosphates (OPs) and carbamates are two major classes of pesticides that inhibit acetylcholinesterase (AChE) enzymes, leading to excessive acetylcholine accumulation at nerve terminals. This results in excessive nicotinic and muscarinic neurostimulations. OPs are triphosphoric esters whereas carbamates are carbamic esters. Both are widely used for agricultural and indoor pest control. However, they differ in their toxicity profiles, with OP effects being less reversible and having more severe subacute and chronic effects than carbamates (Sogorb & Vilanova, 2002). Pyrethroids are synthetic derivatives of pyrethrins, natural compounds found in chrysanthemum flowers. They are carboxylic esters that are considered less toxic to mammals than OPs and carbamates. Pyrethroids are widely used in agriculture and household insecticides because of their effectiveness and relatively low toxicity in humans (Sogorb & Vilanova, 2002).

Neonicotinoids (NEOs) are a newer class of pesticides that are considered the fourth generation of organophosphates, pyrethroids, and carbamates. They are widely used in various crops to control insect pests and are often considered ideal substitutes for more toxic pesticides. However, concerns have been raised regarding their impact on non-target organisms, particularly bees and aquatic animals (Zhang et al., 2022). Organochlorines, although less commonly used now because of environmental concerns, are another class of pesticides that have been widely studied for their persistence in the environment and potential health effects (Ahmad et al., 2006; Ongono et al., 2020). Cross-resistance among different pesticide classes has been observed in some insect populations. For example, a study on *Spodoptera litura* found positive cross-resistance within organophosphates, carbamates, and pyrethroids as well as between endosulfan (an organochlorine) and carbamates (Ahmad et al., 2006). The classification of pesticides into different groups helps understand their modes of action, toxicity profiles, and potential for cross-resistance, which is crucial for developing effective pest management strategies and assessing environmental and health risks (Ongono et al., 2020).

Industrial and agricultural activities contribute significantly to pesticide pollution in effluent systems, posing substantial risks to aquatic environments and human health. Agricultural practices, particularly intensive farming, are major sources of pesticide contamination in waterbodies. These chemicals enter aquatic systems through runoff from agricultural fields, accidental spills, and improper disposal (Inostroza et al., 2023). Industrial activities, including the production and use of pesticides, also contribute to their presence in wastewater and effluent. The impact of pesticide pollution varies across countries because of differences in agricultural systems and policies. A study using a spatial regression discontinuity design found that approximately one-third of the global cross-country differences in pesticide pollution risk can be attributed to variations in countries' agricultural systems and policies (Wuepper et al., 2024). The main factors influencing these differences include pesticide regulations, proportion of organic farming, and types of crops grown. This suggests that national policies and agricultural practices play crucial roles in determining the extent of pesticide pollution in effluent systems. Addressing pesticide pollution in effluent systems requires a multi-faceted approach. Although conventional wastewater treatment methods can remove some contaminants, they may not be fully effective in eliminating persistent pesticides (Crini & Lichtfouse, 2019). Advanced treatment technologies, such as membrane bioreactors and natural polymer-based treatments, show promise for improving the removal of these pollutants (Saravanan et al., 2022).

In addition, implementing stricter regulations on pesticide use, promoting organic farming practices, and encouraging sustainable crop selection can significantly reduce the risk of pesticide pollution in effluent systems (Wuepper et al., 2024). Monitoring pesticide residues in the environment is crucial because of their potentially harmful impacts on human health, wildlife populations, and ecosystems (Munir et al., 2024). The widespread use of pesticides in agriculture has led to their widespread presence in various environmental matrices, including water, soil, and food sources (Liu et al., 2024). This necessitates powerful analytical tools and methods for the qualitative and quantitative monitoring of pesticide residues to ensure food safety and environmental protection (Muggli & Schürch, 2023). The formation of bound pesticide residues in soils presents a unique challenge for monitoring efforts. These residues, which are not extractable with solvents, may escape detection by conventional analytical procedures, potentially underestimating the true environmental impact of pesticides (Khan, 1982). Additionally, the rapid increase in pesticide use in developing nations, particularly Africa, has outpaced the ability to monitor and regulate their application, highlighting the need for improved surveillance and toxicovigilance efforts (Orou-Seko et al., 2024).

Monitoring pesticide residues is also essential for assessing and mitigating potential health risks, including acute and chronic poisoning, cancer, and adverse effects on reproduction and the immune system (Munir et al., 2024). They also play a crucial role in evaluating the effectiveness of pesticide management strategies, supporting the development of sustainable agricultural practices, and informing policy decisions to safeguard both human health and the environment (Liu et al., 2024). Pesticides originates from various sources, including the pharmaceutical, industrial, and agricultural sectors (Sharma et al., 2024). Their pervasive presence in the environment poses significant risks to ecosystems and human health, with potential long-term damage, even at trace levels (Songa & Okonkwo, 2016). The negative impacts of pesticides have been far from reaching. They can cause severe diseases, such as cancer, chronic obstructive pulmonary disease, birth defects, and infertility in humans (Samsidar et al., 2017). In aquatic ecosystems, pesticides can have detrimental effects on organisms and disrupt the food chain (Sharma et al., 2024). The bioaccumulation of pesticides in the environment exacerbates these issues, affecting both terrestrial and aquatic life (Parra-Arroyo et al., 2021). Various analytical methods have been developed for pesticide detection, ranging from conventional to advanced methods.

Traditional methods include gas chromatography (GC), high-performance liquid chromatography (HPLC), and thin-layer chromatography (TLC) (Bhadekar et al., 2011). These approaches offer high sensitivity and selectivity but are often time-consuming, complex, and require expensive instrumentation (Songa & Okonkwo, 2016). Advanced detection methods such as biosensors, immunosensors, and nanosystem-supported techniques have emerged as promising alternatives. These methods provide rapid, sensitive, and cost-effective detection, often allowing for on-site analysis (Kaur et al., 2021). Recent studies have focused on the development of more efficient and environmentally friendly detection techniques. Green analytical methods incorporating nanosystems have shown promise for convenient, fast, and ultrasensitive detection of pesticide residues in food and environmental samples (Kaur et al., 2021). Biosensor strategies, particularly those based on acetylcholinesterase (AChE), have demonstrated potential for multi-analyte screening and portable instrumentation for rapid toxicity testing (Liu et al., 2012; Songa & Okonkwo, 2016).

II. Sources Of Pesticides Contamination

Agricultural runoff

Agricultural runoff that contains excess pesticides from crop production is a significant environmental concern. Pesticides, which are beneficial for crop protection and yield enhancement, can migrate from target fields via runoff and erosion, thereby leading to surface water contamination (Steenhuis & Walter, 1980). This issue is particularly problematic because of the widespread use of pesticides in agriculture, which has been crucial for increasing food production to meet the needs of the growing global population (Tudi et al., 2021). The concentration of pesticides in runoff water can be predicted using semi-empirical formulas, considering factors such as pesticide formulation, application rate, and time between application and runoff events (Wauchope & Leonard, 1980). Interestingly, although pesticides are essential for crop protection, studies have shown that farmers often overuse these chemicals. For instance, research in China revealed that 57%, 64%, and 17% of pesticides used in rice, cotton, and maize production, respectively, were in excess of the optimal amounts (Zhang et al., 2015).

Various mitigation strategies have been explored to address the issue of pesticide runoff. These include the use of vegetated filter strips (VFSs) around culverts draining agricultural fields, which can reduce pesticide and sediment loss (Arpino et al., 2023). Additionally, innovative approaches, such as pesticide-free, non-organic production systems, are gaining traction in Europe as a means of reducing pesticide use while maintaining crop yields (Finger & Möhring, 2024). Furthermore, the potential of constructed wetlands to assimilate and process pesticides from agricultural runoff has been investigated as a promising solution (Rodgers & Dunn, 1992). These strategies, along with the adoption of alternative agricultural practices such as crop rotations and mulch tillage, can help minimize the environmental impact of pesticide runoff while maintaining agricultural productivity (Papendick et al., 1986).

Industrial discharge

Industrial discharge, particularly from manufacturing and formulation industries, is a significant source of pesticide contamination in water bodies. Pesticide manufacturing facilities (PMFs) and pesticide wastewater treatment plants (PWWTPs) have been found to release various pesticides into the environment (Ryu et al., 2022). In a study of 36 pesticides, 32 were detected in PMF wastewater and PWWTP influents, with concentrations reaching 466.8 mg/L (Ryu et al., 2022). The food packaging and processing industries have also been identified as relevant point sources of pesticide contamination, a fact that has not been extensively investigated (Campos-Mañas et al., 2019).

A study on food processing industry effluents revealed the presence of 17 target pesticides and 3 additional pesticides through suspect screening, with imazalil, pyrimethanil, and thiabendazole found at particularly high concentrations (Campos-Mañas et al., 2019). Industrial discharge from the pesticide manufacturing, formulation, and food processing industries contributes significantly to pesticide pollution in water systems. The incomplete removal of pesticides from treatment plants and discharge of effluents containing these contaminants highlight the need for more effective treatment technologies and stricter regulations to mitigate the environmental impact of industrial pesticide discharge (Campos-Mañas et al., 2019; Ryu et al., 2022).

Urban sources

Urban sources, particularly domestic pest control and lawn treatment, contribute significantly to the presence of pesticides in industrial and effluent systems. Fipronil and imidacloprid, commonly used in urban pest control, have been detected in most wastewater samples (>70%) in multiple studies (Budd et al., 2023; Sadaria et al., 2016). These pesticides, along with pyrethroids, were found in influent and lateral samples, indicating their widespread use in urban environments. While some pesticides, such as pyrethroids, were effectively removed during wastewater treatment, more hydrophilic compounds, such as imidacloprid and fiproles, persisted and were detected in effluent samples (Budd et al., 2023; Sadaria et al., 2016).

This highlights the challenge of eliminating these substances completely through conventional treatment processes. Additionally, a study focusing on Australian wastewater treatment plants found that approximately 33 tons of targeted pesticides enter WWTP influent annually nationwide, with 14 tons emitted in effluents (Knight et al., 2023). Urban sources, particularly domestic pest control and lawn treatment, are significant contributors to pesticide contamination in wastewater systems. The persistence of certain pesticides through treatment processes underscores the need for improved source control measures and more effective treatment technologies to mitigate their environmental impacts.

Wastewater treatment plants

Wastewater treatment plants (WWTPs) have been identified as significant sources of pesticides in the environment, owing to their incomplete degradation and persistence in effluents. Studies have shown that Many pesticides are not effectively removed during conventional wastewater treatment processes, leading to their release into receiving water bodies (Köck-Schulmeyer et al., 2013). In a study examining 22 selected pesticides in three different WWTPs, the total pesticide levels were generally below 1 μg/L in wastewater. However, the removal rates were variable and often poor, with some pesticides showing higher concentrations in the effluent than in the influent. This unexpected increase could be attributed to factors such as deconjugation of metabolites, hydrolysis, and desorption from particulate matter during treatment (Köck-Schulmeyer et al., 2013).

The most frequently detected and environmentally relevant pesticides are diazinon and diuron, followed by atrazine, simazine, and malathion. The persistence of pesticides in WWTP effluents is concerning because of their potential impact on human and ecosystem health. Non-targeted analysis of WWTP effluents has revealed the presence of numerous persistent compounds, including some that have not been previously reported in effluents or water-reuse systems (Mladenov et al., 2021). This highlights the need for improved monitoring and treatment strategies to address pesticide contamination in WWTPs.

Leachates from landfills

Landfill leachates have been identified as a significant source of pesticides in industrial and effluent systems, primarily due to the disposal of expired or banned pesticides. Studies have shown that a wide range of hazardous chemicals, including pesticides, are found in landfill leachates (Slack et al., 2004). These contaminants originate from household hazardous waste (HHW), which includes garden pesticides and other potentially harmful substances disposed of in municipal landfills. Interestingly, the presence of organochlorine pesticides has been specifically observed in landfill leachates (Oturan et al., 2015). This finding highlights the persistence of these compounds and their potential to contaminate the surrounding environment long after disposal.

Furthermore, the treatment of landfill leachates has proven challenging, with some conventional methods being ineffective in removing these persistent organic pollutants (Lu et al., 2016; Oturan et al., 2015). The disposal of expired or banned pesticides in landfills significantly contributes to the presence of these compounds in industrial and effluent systems. The leaching of these chemicals from landfills poses a potential risk to soil and groundwater quality (Lu et al., 2016). Therefore, improved waste management practices and more effective leachate treatment technologies are necessary to mitigate the environmental impact of pesticides from landfill sources.

III. Negative Impacts Of Pesticides

Environmental Effects

Contamination of surface water and groundwater

Pesticides have significant negative environmental effects, particularly when contaminating surface water and groundwater. Pesticides from agricultural runoff and other sources can enter both surface and groundwater systems, posing risks to aquatic ecosystems and human health (Li & Zhang, 1999; Mcknight et al., 2015). Contamination of water resources by pesticides is widespread and occurs through various pathways. Surface runoff from agricultural fields can carry pesticides into streams and rivers, whereas groundwater contamination often results from pesticide leaching through the soil (Mcknight et al., 2015). In some cases, groundwater itself can become a source of pesticide contamination of surface water, highlighting the interconnected nature of these water systems (Mcknight et al., 2015).

The impact of pesticide contamination is not limited to the use of pesticides. Legacy pesticides, their metabolites, and impurities also contribute significantly to the overall toxicity in aquatic environments (Mcknight et al., 2015). This persistence of pesticides in the environment, coupled with their potential for bioaccumulation, raises concerns about long-term ecological effects. Additionally, contamination of groundwater by pesticides is particularly problematic because of the slow movement and long residence times of groundwater, which can lead to prolonged exposure and difficulty in remediation (Foster et al., 1991). Contamination of surface water and groundwater by pesticides is a serious environmental issue with far-reaching consequences. The presence of both current and legacy pesticides in water resources underscores the need for comprehensive monitoring programs, improved agricultural practices, and effective regulatory measures to mitigate their negative impacts on aquatic ecosystems and ensure the safety of drinking water sources (Li & Zhang, 1999).

Bioaccumulation in aquatic organisms (biomagnification)

Pesticides have significant negative effects on aquatic ecosystems, particularly through bioaccumulation in organisms and subsequent biomagnification in the food web. Aquatic organisms, including fish, crustaceans, and macroinvertebrates, can accumulate pesticides directly from water through their gills or epithelial tissues as well as through dietary exposure (Katagi, 2009).

This bioaccumulation process can lead to pesticide concentrations in tissues of organisms that are much higher than those in surrounding water. The bioaccumulation of pesticides in aquatic organisms is influenced by various factors, including the chemical properties of the pesticides, the characteristics of the organisms, and environmental conditions (Junaid et al., 2023).

For instance, hydrophobic pesticides tend to accumulate more readily in the lipid-rich tissues of aquatic organisms. Biomagnification occurs when pesticide concentrations increase through two or more trophic levels in the food web, resulting in higher concentrations in predators at the top of the food chain (Katagi, 2009). The consequences of pesticide bioaccumulation and biomagnification in aquatic ecosystems are severe and far reaching. Studies have revealed multifaceted effects on aquatic organisms, including growth and reproduction impairments, oxidative stress, altered genetic and enzymatic responses, metabolic abnormalities, multigenerational effects, histopathological modifications, neurotoxicity, and hepatotoxicity (Junaid et al., 2023).

These effects can disrupt the balance of aquatic ecosystems, potentially leading to long-term ecological consequences.

Furthermore, the biomagnification of pesticides in the food web poses risks to higher-level predators, including humans, who consume contaminated aquatic organisms (Saha & Dutta, 2024).The bioaccumulation and biomagnification of pesticides in aquatic ecosystems is a significant environmental concern. These processes not only affect individual organisms, but also have the potential to disrupt entire food webs and ecosystem functions. To address this issue, it is crucial to develop targeted and environmentally friendly pesticides, implement stricter regulations on pesticide use, and continue research on the long-term effects of pesticide accumulation in aquatic environments.

Disruption of non-target species (pollinators, beneficial microorganisms)

Pesticides have significant negative environmental impacts, particularly on non-target species such as pollinators and beneficial microorganisms. These chemicals can disrupt ecosystems by affecting various parameters of the animal microbiome, including the taxonomic composition, bacterial biodiversity, and bacterial ratios in organisms ranging from insects to mammals (Syromyatnikov et al., 2020). This disruption can lead to reduced immunity in animals and poses a global threat to pollinators.

The impact on pollinators is of particular concern. Pesticides can affect the intestinal microbiota of bumblebees and bees, increasing their sensitivity to pathogenic microflora, potentially leading to insect death (Syromyatnikov et al., 2020). Moreover, pesticides can impair the cognitive abilities of pollinators, thereby affecting their performance and ultimately impacting colony viability (Sánchez-Bayo et al., 2016). Neonicotinoids and glyphosate, two widely used pesticides, have been shown to reduce sucrose responsiveness and negatively affect olfactory learning in honeybees, which could have repercussions for food distribution, propagation of olfactory information, and task coordination within the nest (Mengoni Goñalons & Farina, 2018).

Pesticide use disrupts non-target species, particularly pollinators and beneficial microorganisms, leading to ecosystem imbalances and potential food chain contamination (Barathi et al., 2023). To mitigate these effects, integrated pest management techniques, the development of selective insecticides with reduced environmental persistence, and the promotion of pesticide use are crucial steps towards more sustainable agricultural practices (Barathi et al., 2023).

Soil degradation and loss of microbial diversity

The excessive use of pesticides in modern agriculture has led to the widespread contamination and degradation of agroecosystems (Liu et al., 2020). These chemicals disrupt beneficial soil microflora, potentially spreading dangerous diseases to humans and animals (Sharma et al., 2023). Pesticide accumulation in the soil poses a threat to both soil health and the overall ecosystem, negatively affecting terrestrial and aquatic life as they enter the food chain and water systems (Sharma et al., 2023). Studies have reported contradictory results regarding the effects of pesticides. For instance, certain pesticides (chlorpyrifos and fosthiazate) increase soil microbial parameters, whereas others (dimethoate) decrease them (Eisenhauer et al., 2009). Additionally, some microorganisms, including nitrogen-fixing bacteria called diazotrophs, have shown natural tolerance to pesticides, and can even contribute to the biodegradation of toxic compounds (Sharma et al., 2023).

While pesticides can have detrimental effects on soil health and microbial diversity, their impacts are complex and can vary depending on specific chemicals and environmental conditions. The loss of soil microbial diversity due to pesticide use can significantly impact specialized soil functions, such as pollution remediation and greenhouse gas emissions (Yang et al., 2021). To mitigate these negative effects, sustainable agricultural practices and bioremediation techniques that harness the natural metabolic capabilities of soil microorganisms are being explored to restore soil health and promote long-term agricultural productivity (Oro et al., 2024).

Human Health Risks

Acute toxicity

Pesticides can cause severe acute toxicity leading to neurological disorders, respiratory issues, and skin irritation. Acute exposure to pesticides, particularly organophosphates, such as dichlorvos, can inhibit acetylcholinesterase at cholinergic junctions in the nervous system, resulting in neurological disorders (Okoroiwu & Iwara, 2018). This can manifest as acute short-term effects on both central and peripheral nervous systems (Keifer & Firestone, 2007). Respiratory issues are a common acute effect of pesticide exposure, with chloropicrin causing irritation of the upper respiratory tract, potentially leading to life-threatening edema in severe cases (Pesonen & Vähäkangas, 2020). Skin irritation is also a frequent acute effect, with pesticides causing simple irritation to the skin and eyes upon contact (Rani et al., 2020).

The acute effects of pesticides vary depending on the specific compound and the route of exposure. For instance, fumigants affect the nervous system through toxicological mechanisms that affect most body tissues (Keifer & Firestone, 2007). Additionally, the acute effects of pesticides are not limited to direct exposure, as prenatal and postnatal exposure can lead to adverse health outcomes in children (Rodrigues et al., 2024). Acute toxicity of pesticides manifests primarily as neurological disorders, respiratory issues, and skin irritation. These effects can range from mild irritation to severe life-threatening conditions, highlighting the importance of proper handling and regulation of these chemicals to protect human health.

Chronic exposure (Carcinogenic, endocrine disruption, reproductive toxicity)

Chronic exposure to pesticides has been associated with various adverse health effects including carcinogenicity, endocrine disruption, and reproductive toxicity. Epidemiological studies and animal models have demonstrated that long-term exposure to these chemicals can lead to significant health concerns, particularly in vulnerable populations (Cocco, 2002). Pesticides have been linked to hormone-dependent cancers, such as breast, endometrial, ovarian, prostate, testicular, and thyroid cancers. While recent studies have ruled out DDT derivatives as the primary cause of reproductive organ cancers, high-level exposure to o,p'-DDE may still play a role in post-menopausal ER+ breast cancer (Cocco, 2002). Additionally, pesticides can interfere with the synthesis, secretion, transport, activity, and elimination of natural hormones, potentially leading to a wide range of endocrine-related effects (Schug et al., 2011).

In terms of reproductive toxicity, pesticides have been shown to adversely affect male fertility, particularly in occupational settings. Exposure to certain pesticides, such as DBCP and chlordecone, is associated with reduced sperm count and quality (Cocco, 2002). Furthermore, pesticides can disrupt sperm capacitation, a crucial process in male fertility, potentially leading to infertility (Uwamahoro et al., 2024). Chronic exposure to pesticides may also cause developmental toxicity, carcinogenicity, mutagenicity, immunotoxicity, and neurotoxicity, with estrogenic effects particularly prevalent in pesticides (Choi et al., 2004). These findings underscore the importance of understanding and mitigating the long-term health effects of pesticide exposure.

Presence of pesticide residues in food and drinking water

Pesticide residues in food and drinking water pose significant health risks to humans via various exposure pathways. Long-term exposure to these residues can lead to serious health problems including cancer, endocrine disruption, and neurotoxicity (Sajad et al., 2024). The presence of pesticide residues in soil, water, air, and food may have harmful effects on human and environmental health, even at trace levels (Kookana et al., 1998). Interestingly, although pesticides are widely used to increase food security, their residues have been found in both raw and processed fruits and vegetables (Keikotlhaile et al., 2009). This highlights the contradiction between the intended purpose of pesticides and their potential negative health impacts. Moreover, the accumulation of pesticide residues in food products has been associated with a broad variety of human health hazards, ranging from short-term to long-term toxic effects (Grewal et al., 2017).

Pesticide residues in food and drinking water are a serious public health concern. Although efforts have been made to mitigate their presence, pervasive residues persist in the environment and food (Liu et al., 2024). To address this issue, various methods, such as washing, blanching, peeling, and thermal treatments have been found to be effective in reducing pesticide residues (Mir et al., 2021). Additionally, novel technologies, such as cold plasma and ozone treatment, have shown promising results for pesticide degradation without affecting food quality (Mir et al., 2021). However, further research is needed to develop more effective strategies for pesticide management and explore alternative practices that safeguard both human health and the environment.

IV. Analytical Methods For Pesticides Detection

Spectroscopic Techniques

UV-Vis Spectroscopy

UV-Vis spectroscopy has emerged as a simple yet powerful analytical tool for pesticide analysis, offering rapid and sensitive detection of specific components that are sensitive to ultraviolet irradiation (Li et al., 2020). This technique has experienced remarkable development in recent years, with wide applications in agricultural, food, pharmaceutical, and environmental sciences (Ríos-Reina & Azcarate, 2022). This method is based on measuring the absorbance or transmittance of light passing through a medium as a function of wavelength, making it suitable for a broad range of organic compounds and inorganic species (Rocha et al., 2018).

Despite its simplicity and widespread use, UV-Vis spectroscopy has limitations in terms of sensitivity when compared to more advanced techniques. To address this issue, researchers have explored innovative approaches to enhancing their capabilities. For instance, combining UV-Vis with near-infrared spectroscopy (NIR) and employing data fusion strategies with machine learning algorithms, such as extreme learning machines (ELM), have shown improved predictive ability for pesticide analysis (Li et al., 2020). This approach demonstrated better results than individual methods, with a lower root mean square error of prediction (RMSEP) and higher coefficient of determination (R^2) for deltamethrin formulation analysis.

Although UV-Vis spectroscopy offers a straightforward and cost-effective method for pesticide analysis, its limited sensitivity can be overcome by integrating it with other spectroscopic techniques and advanced data-processing methods. The combination of UV-Vis spectroscopy with chemometrics and data fusion strategies presents a promising direction for enhancing the robustness and accuracy of pesticide detection (Li et al., 2020; Ríos-Reina & Azcarate, 2022). This approach not only improves sensitivity, but also broadens the application range, making UV-Vis spectroscopy a valuable tool for pesticide quality control and on-site monitoring.

Fourier Transform Infrared Spectroscopy (FT-IR)

Fourier-transform infrared (FTIR) spectroscopy has emerged as a powerful analytical technique for the identification and characterization of pesticides. This method is particularly useful for functional group identification and provides valuable information on the molecular structures of pesticide compounds (Enders et al., 2021). FTIR spectroscopy offers a fast and simple approach for analyzing organic samples, making it an attractive option for pesticide analysis in environmental and agricultural research (Yusuf, 2023).

One of the key advantages of FTIR in pesticide analysis is its ability to provide a molecular fingerprint of the sample, allowing for the identification of specific functional groups and chemical bonds present in the pesticide molecules (Al-Kelani & Buthelezi, 2024). However, the interpretation of FTIR spectra for pesticides can be complex and time-consuming, and often requires expertise in spectral analysis (Enders et al., 2021). To address this challenge, recent advancements in machine learning algorithms such as convolutional neural networks (CNNs) have been developed to automate and expedite the process of functional group identification from FTIR spectra (Enders et al., 2021).

Although FTIR spectroscopy offers significant potential for pesticide analysis through functional group identification, the complexity of data interpretation remains a challenge. The integration of machine learning approaches with FTIR techniques shows promise in overcoming this limitation, potentially enhancing the efficiency and accuracy of pesticide analysis in various environmental and agricultural applications (Al-Kelani & Buthelezi, 2024; Enders et al., 2021).

Chromatographic Techniques

Thin Layer Chromatography (TLC)

Thin-layer chromatography (TLC) has emerged as a valuable technique for pesticide analysis, offering unique advantages for qualitative analysis and rapid screening. TLC's open stationary phase of TLC allows for the presentation of results as a stored image, making it particularly useful for visual interpretation and documentation (Sherma, 2017). This characteristic makes TLC an excellent tool for rapid screening of pesticide mixtures, enabling researchers to quickly identify the presence of various compounds.

The combination of TLC with surface-enhanced Raman scattering (SERS) detection has further enhanced its pesticide analysis capabilities. By assembling monolayer Ag nanoparticles on TLC plates, researchers have developed a method that can successfully classify and locate different pesticides in mixtures with 100% accuracy (Fang et al., 2024). This innovative approach demonstrates the potential of TLC to address the challenges of identifying components in complex pesticide mixtures.

However, it is important to note that while TLC excels in qualitative analysis and rapid screening, it generally lacks the quantification accuracy of advanced chromatographic techniques. For instance, high-performance liquid chromatography (HPLC) is often preferred for precise quantitative analysis owing to its highly efficient separation and high detection sensitivity (Gupta et al., 2022). Nevertheless, recent advancements, such as digitally enhanced TLC (DE-TLC), have shown promise in improving quantitative analysis capabilities using regular TLC equipment combined with digital photography and software analysis (Hess, 2007). This development may help bridge the gap between TLC's qualitative strengths of TLC and its quantitative limitations in pesticide analyses.

High-Performance Liquid Chromatography (HPLC)

High-performance liquid chromatography (HPLC) has emerged as a powerful and versatile technique for pesticide analyses. It offers several advantages over traditional methods, including high sensitivity, selectivity, and the ability to simultaneously analyze a wide range of pesticides simultaneously (Farran et al., 1996). HPLC has been successfully applied to various pesticide classes such as triazines, phenylureas, carbamates, and organophosphorus compounds (Farran et al., 1996; Osselton & Snelling, 1986).

One of the key strengths of HPLC for pesticide analysis is its compatibility with different detection methods. For instance, HPLC coupled with diode-array spectrophotometric detection has been used to analyze 51 common pesticides, providing valuable chromatographic properties for identification (Osselton & Snelling, 1986). Additionally, the combination of HPLC with tandem mass spectrometry (HPLC/MS/MS) has enabled the quantification of urinary metabolites of pesticides like atrazine, malathion, and 2,4-D with detection limits below 0.5 μg/L (Beeson et al., 1999).

Despite its advantages, HPLC may not always be sufficiently sensitive for environmental analysis without additional sample preparation steps (Farran et al., 1996). To address this limitation, researchers have explored various concentration methodologies, such as offline solid extraction using carbopack columns, which can detect low ppb levels of individual pesticides (Farran et al., 1996). Another approach involves the use of continuous flow microextraction (CFME) combined with HPLC-UV detection, achieving detection limits lower than 4 ng/ml for five widely used pesticides in water samples (He & Lee, 2006).

HPLC is a valuable tool for pesticide analysis, offering high sensitivity, selectivity, and versatility. Its compatibility with various detection methods and sample preparation techniques makes it suitable for a wide range of pesticide research and monitoring applications. However, ongoing research continues to focus on improving the sensitivity and developing novel approaches to enhance the capabilities of HPLC in pesticide analysis (Braga et al., 2007; Christopher et al., 2020; He & Lee, 2006).

Gas Chromatography (GC) with Electron Capture Detector (ECD)

Gas Chromatography (GC) coupled with electron capture detector (ECD) has emerged as a powerful analytical technique for pesticide analysis, particularly for chlorinated compounds. This method offers excellent sensitivity and selectivity for electron-capturing molecules, making it highly suitable for detecting trace pesticide levels in various environmental matrices (Boussahel et al., 2002; Vidal et al., 1999). GC-ECD has been successfully applied to the analysis of a wide range of pesticides, including chlorinated pesticides, phenylarsenic compounds, and fipronil and its metabolites (Boussahel et al., 2002; Haas et al., 1998; Li et al., 2020). This technique has demonstrated good reproducibility, low detection limits, and wide linear ranges, making it a reliable choice for water quality control and environmental monitoring (Boussahel et al., 2002).

GC-ECD, in some cases, has shown detection limits as low as 0.001-1 ppb for certain pesticides (Liška & Slobodník, 1996). While GC-ECD is highly effective for the detection of many pesticides, it is not universally applicable. LC is the preferred method for polar, non-volatile, and thermolabile compounds, liquid chromatography (LC) may be the preferred method (Liška & Slobodník, 1996). In addition, the stability of certain pesticides during chromatographic determination is a concern, as noted in the analysis of captan (Hughes et al., 2006). GC-ECD remains a cornerstone technique for pesticide analysis because of its high sensitivity, selectivity, and efficiency. Its advantages include high separation efficiency, high analysis speed, and the availability of highly sensitive detectors (Liška & Slobodník, 1996). However, it is important to note that no single technique has overall priority in the environmental analysis of pesticides, and GC-ECD should be considered complementary to other methods such as GC-MS and LC-MS (Liška & Slobodník, 1996). The choice of technique depends on the specific analytes and matrices under investigation.

Gas Chromatography-Mass Spectrometry (GC-MS)

Gas Chromatography-Mass Spectrometry (GC-MS) is a cornerstone technique for pesticide analysis that offers high sensitivity and selectivity. Recent advancements in GC-MS technology, including atmospheric pressure ionization sources, fast GC, GC × GCxGC, and high-resolution mass spectrometry, have significantly enhanced its capabilities (Pico et al., 2019). Although liquid chromatography-mass spectrometry (LC-MS/MS) is now often preferred, GC-MS remains particularly effective for analyzing pyrethroids and organochlorine pesticides, as well as many other pesticides that perform well with both techniques (Pico et al., 2019).

GC-MS can be applied with different ionization modes for the confirmatory analysis of various pesticide classes. For instance, electron impact (EI) is commonly used for all pesticides, while positive-ion chemical ionization (PCI) is recommended for chlorotriazines and negative-ion chemical ionization (NCI) for organophosphorus pesticides (Durand & Barceló, 1991). This versatility allows for comprehensive pesticide residue analysis in complex matrices, such as soil samples, with detection limits ranging from 5 $\mu g\ g^{-1}$ to 9 $\mu g\ g^{-1}$ (Durand & Barceló, 1991).

GC-MS remains a vital analytical tool for pesticide residue determination and offers a range of approaches to suit different analytical needs. Its ability to analyze multiple pesticide classes, coupled with recent technological advancements, ensures its continued relevance in the field. As the technique evolves, it is likely to maintain its importance in pesticide analysis, complementing other analytical methods and contributing to more comprehensive and accurate pesticide residue determination (Durand & Barceló, 1991; Pico et al., 2019).

Electrochemical Methods

Differential Pulse Voltammetry (DPV)

Differential Pulse Voltammetry (DPV) has emerged as a powerful electrochemical technique for pesticide analysis that offers high sensitivity and selectivity. This method has been successfully applied to detect various pesticides, including carbamates and paraquat, in different matrices such as water and food samples (Chuntib et al., 2017; Costa et al., 2017; Pop et al., 2017). DPV has demonstrated superior performance compared with other voltammetric techniques for pesticide analysis. For instance, in the detection of methomyl, a carbamate pesticide, DPV exhibited a lower detection limit (1.2×10^{-6} mol L^{-1}) than square wave voltammetry (1.9×10^{-5}

mol L^{-1}) (Costa et al., 2017). Similarly, for paraquat detection, DPV coupled with a screen-printed carbon electrode modified with carbon nanotubes achieved a detection limit of 0.17 µM (Chuntib et al., 2017).

Most importantly, the effectiveness of DPV for pesticide analysis extends beyond that of conventional electrodes. A study using a graphene-modified boron-doped diamond electrode demonstrated remarkable sensitivity for the simultaneous detection of carbaryl and paraquat in apple juice, with sensitivities of 33.27 µA μM^{-1} cm^{-2} and 31.83 µA μM^{-1} cm^{-2}, respectively (Pop et al., 2017). This highlights the potential of DPV for pesticide detection in food samples in real-world applications. DPV has proven to be a versatile and sensitive technique for pesticide analysis, capable of simultaneously detecting multiple pesticides in various matrices. Its superior performance coupled with the use of modified electrodes makes it a promising tool for rapid and cost-effective pesticide monitoring in environmental and food safety applications.

Bioanalytical Techniques

Enzyme-Linked Immunosorbent Assay (ELISA)

Enzyme-Linked Immunosorbent Assay (ELISA) is a powerful bioanalytical technique widely used for the analysis of pesticides because of its high sensitivity, specificity, and throughput (Hu et al., 2024). This immunological assay relies on the interaction between the antigen (target pesticide) and specific antibodies, with the presence of the antigen confirmed through the enzyme-linked antibody catalysis of a substrate (Hayrapetyan et al., 2023). In the context of pesticide analysis, enzyme-linked immunosorbent assays ELISA have demonstrated their effectiveness in detecting and quantifying various compounds. For instance, a kit-based ELISA for determining dinotefuran residues in rice samples showed high sensitivity, with a detection limit of 0.6 ng/mL and a dynamic range from 1.0 to 30 ng/mL (Watanabe et al., 2011). The assay exhibited good recoveries ranging from 92.5% to 113.2%, with coefficients of variation below 10%, indicating its reliability for pesticide residue analysis.

As much as ELISA are widely used, there are ongoing efforts to improve their performance and expand their capabilities. For example, researchers have developed novel approaches such as the bioluminescent-bacteria-linked immunosorbent assay (BBLISA), which utilizes bioluminescent bacteria and metallic nanoparticles as an alternative to traditional enzyme-based detection (Hu et al., 2024). Additionally, the incorporation of nanomaterials, such as MnO2 nanowires, has been explored to enhance the sensitivity and specificity of ELISAs for detecting toxicologically important substances in complex biological systems (Wan et al., 2012). Enzyme-linked immunosorbent assay (ELISA) remains a valuable tool for pesticide analysis, offering a quick, simple, and reliable method for residue detection. Its adaptability to various formats and continuous improvements in sensitivity and specificity make it an essential tool for ensuring food safety and environmental monitoring (Watanabe et al., 2011). As research progresses, the integration of novel materials and detection methods is likely to further enhance the capabilities of ELISA in pesticide analysis.

Biosensors (Enzyme, DNA, or Immunosensors)

Biosensors have emerged as promising bioanalytical techniques for pesticide analysis, offering rapid, sensitive, and cost-effective alternatives to the traditional chromatographic methods. Enzyme-based biosensors, particularly those that utilize cholinesterases, have been extensively developed for the detection of organophosphates and carbamates (Trojanowicz, 2002). These sensors exploit the inhibitory effects of pesticides on enzyme activity, providing a "biologically relevant" detection mechanism (Bucur et al., 2018). DNA biosensors and aptasensors have also shown potential for pesticide analysis, with screen-printed electrodes (SPEs) being a popular platform for their development (Taleat et al., 2014). Immunosensors, which exploit the high specificity of antibody-antigen interactions, have been used to detect various pesticides, toxins, and microorganisms (Jain et al., 2017; Taleat et al., 2014).

Recent advances in biosensor technology have focused on enhancing sensitivity and selectivity through the incorporation of nanomaterials, such as metal nanoparticles, carbon nanotubes, and graphene (Hassani et al., 2016). The integration of recombinant enzyme mutants and the development of biosensor arrays combined with artificial neural networks have improved detectability and enabled multicomponent determination (Bucur et al., 2018; Trojanowicz, 2002). Although biosensors offer numerous advantages, including on-site analysis capabilities and portability, challenges remain in improving their specificity, sensitivity, reproducibility, and stability for routine analysis (Wang & Wang, 2008). Future developments in the field are likely to focus on creating field-portable devices and multiplexing analysis systems to meet the growing demand for rapid and accurate in situ pesticide detection (Taleat et al., 2014)

V. Conclusion

Pesticides are classified based on their chemical structure and mode of action, and are widely used in agriculture and pest control. Organophosphates, carbamates, pyrethroids, neonicotinoids, and organochlorines are the major pesticide classes with varying toxicity profiles. Pesticide pollution in effluent systems originates from agricultural runoff, industrial discharge, urban sources, wastewater treatment plants, and landfill leachate.

Pesticides have significant negative environmental impacts, including the contamination of surface water and groundwater, bioaccumulation in aquatic organisms, disruption of non-target species, and soil degradation. Human health risks associated with pesticide exposure include acute toxicity; chronic effects such as carcinogenicity, endocrine disruption, and reproductive toxicity; and the presence of pesticide residues in food and drinking water. Various analytical methods are used for pesticide detection, including spectroscopic techniques (UV-Vis and FT-IR), chromatographic techniques (TLC, HPLC, GC-ECD, and GC-MS), electrochemical methods (DPV), and bioanalytical techniques (ELISA and biosensors). Each method has strengths and limitations, and the choice of technique depends on the specific analytes and matrices under investigation.

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