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Chemistry, Environmental Fate, Toxicological Implications, and Sustainable Management of Pesticides and Herbicides in Commercial Agriculture in Nigeria: A Review

Oladapo, F. O.
Department of Chemical Sciences, Tai Solarin Federal University of Education, Ijagun, Ogun State, Nigeria
Corresponding email: *Oladapofo@tasued.edu.ng*

Abstract
Pesticides and herbicides play a critical role in commercial agriculture by enhancing crop productivity, reducing pest- and weed-related losses, and supporting food security. In Nigeria, increasing agricultural intensification has led to widespread use of diverse agrochemical classes, including organophosphates, carbamates, pyrethroids, organochlorines, neonicotinoids, glyphosate, atrazine, and 2,4-dichlorophenoxyacetic acid (2,4-D). This review examines the chemistry of these agrochemicals, with emphasis on their molecular structures, physicochemical properties, mechanisms of action, environmental behaviour, residue dynamics, toxicological effects, and management challenges within Nigerian agricultural systems. The biological activity of pesticides and herbicides is fundamentally determined by specific chemical interactions with enzymes, receptors, ion channels, and metabolic pathways, while their environmental fate is influenced by hydrolysis, photolysis, oxidation–reduction reactions, sorption, volatilisation, leaching, and runoff processes. Evidence from Nigerian agricultural regions indicates intensive agrochemical application in vegetable production systems, irrigated farming areas, and cocoa plantations, often resulting in detectable residues in soils, water bodies, and agricultural commodities. Analytical chemistry techniques such as gas chromatography–mass spectrometry (GC–MS), liquid chromatography–tandem mass spectrometry (LC–MS/MS), and QuEChERS-based extraction methods have significantly improved residue detection and monitoring capabilities, although analytical infrastructure and surveillance systems remain inadequate in many parts of the country. Human exposure occurs primarily through dermal contact, inhalation, and dietary intake, with toxicological consequences including cholinesterase inhibition, oxidative stress, endocrine disruption, neurological impairment, and developmental toxicity. Persistent challenges such as weak regulatory enforcement, counterfeit pesticide circulation, poor storage practices, limited farmer training, low adoption of Integrated Pest Management (IPM), and insufficient residue monitoring continue to compromise sustainable agrochemical use. Future directions should focus on expanding IPM implementation, developing biopesticides, adopting precision agriculture technologies, strengthening regulatory frameworks, enhancing analytical chemistry capacity, and improving public health education. A comprehensive understanding of agrochemical chemistry is essential for balancing agricultural productivity with environmental protection and human health, thereby promoting sustainable agricultural development in Nigeria.

Keywords: Agrochemicals, pesticides, herbicides, environmental chemistry, toxicological chemistry, pesticide residues, analytical chemistry, commercial agriculture, Nigeria

1. Introduction

Agriculture remains a major economic activity in Nigeria, employing over 35% of the labour force and contributing significantly to rural livelihoods. However, pest infestations, weed competition, and plant diseases cause estimated yield losses of 20–40% annually in staple crops. To address these losses, synthetic pesticides and herbicides have become integral to commercial farming systems. According to field surveys conducted in southwestern Nigeria, over 70% of vegetable farmers apply chemical pesticides weekly during peak growing seasons (Babalola et al., 2019). Similar trends have been reported in northern Nigeria, particularly in irrigated rice and tomato production systems. Chemically, these compounds are designed to disrupt specific biological pathways in pests and weeds. However, their incomplete selectivity and environmental mobility result in unintended exposure to non-target organisms, including humans.

2. Chemical Composition and Classification of Agrochemicals

2.1 Pesticides

Pesticides are chemically diverse bioactive compounds designed to control, repel, or eliminate agricultural pests through specific molecular interactions with biological systems (Casida & Durkin, 2013). From a chemical standpoint, their efficacy is governed by functional group composition, stereochemistry, lipophilicity, and environmental stability, all of which influence receptor binding, metabolic breakdown, and persistence in environmental compartments (Sharma et al., 2019; World Health Organization [WHO], 2020). In commercial agriculture in Nigeria, pesticide use is

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dominated by several major chemical classes, including organophosphates, carbamates, pyrethroids, and organochlorines, each exhibiting distinct structural frameworks and reaction mechanisms that determine both biological activity and environmental fate (Food and Agriculture Organization [FAO] and World Health Organization [WHO], 2022-2024; Popp et al., 2013). These differences are central to understanding variability in toxicity profiles, resistance development in target species, and residual accumulation in soil and water systems (Sharma et al., 2019).

2.1.1 Organophosphate Pesticides

Organophosphates are among the most extensively applied insecticide classes in Nigerian agriculture, particularly in intensive vegetable, maize, and cocoa production systems. Chemically, they are esters or thioesters of phosphoric, phosphonic, or phosphorothioic acids, characterised by a pentavalent phosphorus centre (P(V)) adopting a tetrahedral geometry, typically bonded to oxygen (P=O) or sulfur (P=S), alongside alkoxy (–OR), aryloxy, and various leaving groups that modulate hydrolytic stability and bioactivation potential (Casida & Durkin, 2013; Elersek & Filipic, 2011).

Their biological activity is fundamentally governed by the electrophilicity of the phosphorus atom, which facilitates nucleophilic attack by the serine hydroxyl group in the active site of acetylcholinesterase (AChE). This results in phosphorylation of the enzyme and formation of a highly stable phosphoester bond, inhibiting acetylcholine hydrolysis and leading to synaptic accumulation and cholinergic overstimulation (Sogorb & Vilanova, 2002). Oxon derivatives (P=O forms) are generally more potent than their thiono (P=S) precursors due to enhanced electrophilic character following metabolic activation.

Common representatives such as chlorpyrifos and diazinon are widely used in Nigeria. Field studies have consistently linked these compounds to acute poisoning incidents in rural farming communities, often exacerbated by dermal absorption due to limited use of personal protective equipment (PPE) and their moderate lipophilicity (Sharma et al., 2019).

Compounds such as chlorpyrifos and diazinon are widely used in cocoa, maize, and vegetable farms.

Organophosphates account for a significant proportion of pesticide poisoning cases in rural hospitals in northern Nigeria, with some studies attributing up to 40% of acute pesticide-related admissions to this class (Okoffo et al., 2016).

2.1.2 Carbamate Pesticides

Carbamates are esters of carbamic acid containing the functional group –O–C(=O)–NH–, and are structurally diverse, often incorporating aromatic or aliphatic substituents that influence volatility, hydrolysis kinetics, and soil adsorption behaviour (Ware & Whitacre, 2004). Compared with organophosphates, carbamates exhibit increased hydrolytic lability due to the inherent instability of the carbamate ester linkage under environmental pH and temperature fluctuations.

Their mechanism of toxicity involves reversible carbamylation of the serine hydroxyl group in acetylcholinesterase, forming a transient enzyme–inhibitor complex that undergoes spontaneous hydrolysis, restoring enzymatic activity over time (Elersek & Filipic, 2011). This reversible binding accounts for their comparatively shorter duration of toxic action.

Carbaryl and carbofuran remain widely used in Nigerian vegetable farming systems due to their rapid insecticidal knockdown and moderate environmental persistence. However, improper dosing and lack of calibration in application equipment significantly increase exposure risk among users (Okoffo et al., 2016).

2.1.3 Pyrethroid Pesticides

Pyrethroids are synthetic analogues of naturally occurring pyrethrins and are structurally defined by ester linkages between a cyclopropane carboxylic acid moiety and an alcohol component. Their molecular architecture often includes stereochemically complex cyclopropane rings and halogenated aromatic systems, typically chlorinated or brominated, which enhance insecticidal potency and environmental stability (Richardson et al., 2019).

Their mode of action involves binding to voltage-gated sodium channels (Nav channels), where they inhibit channel inactivation, prolonging sodium influx and causing repetitive neuronal firing, membrane depolarisation, and eventual paralysis (Davies et al., 2007). Stereochemistry plays a crucial role, as cis-isomers generally exhibit higher biological activity than trans-isomers.

Compounds such as cypermethrin and permethrin are extensively used in Nigeria due to their affordability and relatively low acute mammalian toxicity. Their high hydrophobicity (log Kow > 4) promotes strong sorption to soil organic matter and plant cuticles, reducing aqueous mobility but increasing persistence in sediment and biotic lipid compartments (Sanchez-Bayo & Wyckhuys, 2019).

2.1.4 Organochlorine Pesticides

Organochlorines such as dichlorodiphenyltrichloroethane (DDT) and lindane are highly chlorinated aromatic or alicyclic compounds characterised by strong carbon–chlorine bonds with low susceptibility to hydrolysis, photolysis, or microbial degradation (ATSDR, 2002). Their structural stability arises from extensive halogenation, which increases molecular lipophilicity and decreases reactivity.

These properties result in pronounced environmental persistence and biomagnification through trophic levels. Despite regulatory restrictions, residues of organochlorines continue to be detected in soils and aquatic systems in parts of Nigeria, reflecting historical application and possible illegal use (Desforges et al., 2018). Their accumulation in adipose tissue is driven

by high octanol–water partition coefficients and metabolic resistance.

2.1.5 Neonicotinoid Pesticides

Neonicotinoids, including imidacloprid and thiamethoxam, are systemic insecticides structurally based on nitroguanidine or cyanoamidine pharmacophores linked to heterocyclic scaffolds such as pyridine or thiazole rings. These structural features confer high aqueous solubility and systemic mobility within plant vascular systems (Simon-Delso et al., 2015, Pisa et al., 2021).

Their mechanism involves agonistic binding to insect nicotinic acetylcholine receptors (nAChRs), causing persistent receptor activation, neuronal depolarisation, and eventual synaptic failure. Unlike mammalian acetylcholine receptors, insect nAChRs exhibit higher affinity for neonicotinoids due to differences in receptor subunit composition (Tomizawa & Casida, 2005).

Although generally less persistent in soil than organochlorines, concerns persist regarding chronic sub-lethal toxicity to pollinators and aquatic invertebrates, particularly given their water solubility and mobility in irrigation systems.

2.2 Herbicides

Herbicides constitute a structurally diverse class of agrochemicals designed to interfere with essential physiological and biochemical pathways in plants. From a chemical standpoint, their activity is governed by functional group reactivity, ionisation behaviour (pKa), stereoelectronic distribution, lipophilicity (log Kow), and their affinity for soil and sediment phases, all of which determine bioavailability, transport, and persistence in agroecosystems (Hanson & Solomon, 2016; Shaner, 2014).

2.2.1 Glyphosate (N-(phosphonomethyl)glycine)

Glyphosate is a broad-spectrum, non-selective herbicide and one of the most widely used agrochemicals globally, particularly in cassava, maize, and plantation agriculture systems. Structurally, it is a small, highly polar aminophosphonic acid containing a carboxyl group, a secondary amine, and a phosphonate moiety, giving rise to multiple dissociation constants (pKa values) and strong chelating behaviour with divalent metal ions such as Ca^{2+} and Mg^{2+} (Duke, 2020).

Chemically, its herbicidal activity arises from competitive inhibition of 5-enolpyruvylshikimate-3-phosphate synthase (EPSPS), a key enzyme in the shikimate pathway responsible for aromatic amino acid biosynthesis in plants and microorganisms. The molecule mimics phosphoenolpyruvate, binding at the EPSPS active site and forming a stable enzyme–inhibitor complex that disrupts metabolic flux toward phenylalanine, tyrosine, and tryptophan synthesis (Steinrücken & Amrhein, 1980).

Due to its high polarity (log Kow approximately −3 to −2) and strong soil adsorption to iron and aluminium oxides, glyphosate is generally considered immobile in soils. However, environmental monitoring in Nigeria has reported its presence in surface waters of agricultural regions at concentrations ranging from 0.01 to 0.35 mg/L, reflecting runoff and erosion-driven transport during rainfall events (Adeniyi & Okedeyi, 2020). Its environmental fate is strongly influenced by microbial degradation to aminomethylphosphonic acid (AMPA), a persistent metabolite with comparable environmental relevance.

2.2.2 Atrazine (6-chloro-N-ethyl-N′-isopropyl-1,3,5-triazine-2,4-diamine)

Atrazine is a chlorinated s-triazine herbicide characterised by a heteroaromatic 1,3,5-triazine ring substituted with chlorine and alkylamino side chains. Its chemical structure confers moderate hydrophobicity (log Kow ~2.6) and relatively high chemical stability under environmental conditions, particularly in neutral to alkaline soils (Jablonowski et al., 2011).

Atrazine acts by binding to the D1 protein (psbA gene product) in photosystem II, inhibiting electron transport at the QB binding site. This prevents plastoquinone reduction and disrupts photophosphorylation, leading to the accumulation of reactive oxygen species (ROS) and oxidative damage to chloroplast membranes (Fuerst & Norman, 1991).

Despite regulatory restrictions in several jurisdictions, atrazine continues to be reported in parts of Nigeria. Its moderate sorption coefficient (Koc) and relatively long half-life under tropical conditions facilitate leaching into groundwater systems, particularly in sandy or low organic matter soils. Its persistence is further influenced by hydrolysis resistance and limited photodegradation once incorporated into soil matrices.

2.2.3 2,4-Dichlorophenoxyacetic acid (2,4-D)

2,4-D is a systemic phenoxyacetic acid herbicide widely applied in cereal production systems for selective control of broadleaf weeds. Structurally, it consists of a dichlorinated aromatic ring linked via an ether bond to an acetic acid side chain, which confers weak acid behaviour (pKa ≈ 2.6) and pH-dependent ionisation in environmental media (Grossmann, 2024).
Its herbicidal activity is based on its function as a synthetic auxin, mimicking indole-3-acetic acid (IAA), the primary endogenous plant growth hormone. At the molecular level, 2,4-D dysregulates gene expression involved in cell elongation, division, and vascular differentiation, leading to uncontrolled growth, vascular collapse, and eventual plant death. The compound interacts with auxin receptors, such as TIR1/AFB complexes, triggering aberrant ubiquitin-mediated protein degradation pathways (Woodward & Bartel, 2005).

The environmental behaviour of 2,4-D is strongly pH-dependent. In acidic soils, the non-ionised form

predominates, increasing sorption to organic matter and reducing mobility. Conversely, in alkaline conditions, the anionic form dominates, enhancing leaching potential. Its degradation is primarily microbial, with half-life variability strongly influenced by temperature, soil moisture, and microbial community structure, making its persistence moderate but highly site-specific.

3. Mechanisms of Action: Chemical Basis of Toxicity

Agrochemical toxicity is fundamentally determined by molecular structure, electronic distribution, and functional group reactivity, which together govern binding affinity to biological macromolecules and the stability of resulting ligand–target complexes. From a chemical perspective, most pesticide modes of action arise from either covalent modification of enzymes, reversible non-covalent binding to receptor sites, or interference with electron-transfer and redox systems essential for energy transduction (Casida & Durkin, 2013; Sogorb & Vilanova, 2002).

3.1 Organophosphates

Organophosphates exert toxicity through covalent phosphorylation of the active-site serine residue in acetylcholinesterase (AChE). The electrophilic phosphorus centre, typically in a P(V) oxidation state, is rendered highly susceptible to nucleophilic attack due to the presence of electron-withdrawing substituents such as alkoxy or aryloxy groups and, in many cases, thiono-to-oxo metabolic activation (P=S → P=O) which increases electrophilicity (Elersek & Filipič, 2011).

The serine hydroxyl group performs a nucleophilic attack on the phosphorus atom, forming a stable phosphoester bond and yielding a phosphorylated enzyme that undergoes extremely slow or irreversible hydrolysis (“aging” via dealkylation). This prevents acetylcholine breakdown at cholinergic synapses, resulting in sustained receptor activation and disruption of ion channel-mediated neurotransmission (Sogorb & Vilanova, 2002). The overall toxicity is therefore governed by phosphorus centre reactivity, leaving group stability, and steric accessibility of the active site.

3.2 Carbamates

Carbamates act through carbamylation of the same serine hydroxyl residue in acetylcholinesterase, but form a tetrahedral carbamyl-enzyme intermediate that is significantly less stable than the phosphorylated analogue. The carbonyl carbon in the carbamate functional group (–O–C(=O)–NH–) is electrophilic but less reactive than phosphorus centres, resulting in a lower activation barrier for reversible binding (Elersek & Filipic, 2011).

Hydrolysis of the carbamylated enzyme occurs spontaneously in aqueous biological environments, restoring enzymatic activity over time. Consequently, toxicity is transient and closely linked to the hydrolytic stability of the carbamate ester bond, which is influenced by electronic substituent effects and steric hindrance around the carbonyl centre.

3.3 Pyrethroids

Pyrethroids disrupt neuronal excitability by modifying the gating kinetics of voltage-gated sodium channels (Nav channels). Their mechanism is primarily non-covalent, involving hydrophobic and van der Waals interactions between the lipophilic ester-containing molecule and the channel protein embedded within the neuronal lipid bilayer (Davies et al., 2007).

The cyclopropane carboxylate moiety and halogenated aromatic ring system confer conformational rigidity and high lipophilicity, enabling membrane partitioning and prolonged residence time at the channel site. This results in delayed channel inactivation, sustained sodium influx, and repetitive depolarisation of neuronal membranes. Stereochemical configuration (cis/trans isomerism) significantly influences binding affinity and toxic potency, reflecting the spatial complementarity between pyrethroid conformers and channel binding domains.

3.4 Glyphosate

Glyphosate toxicity in plants arises from competitive inhibition of 5-enolpyruvylshikimate-3-phosphate synthase (EPSPS), a key enzyme in the shikimate pathway responsible for aromatic amino acid biosynthesis. Chemically, glyphosate acts as a structural analogue of phosphoenolpyruvate (PEP), with its phosphonate and carboxylate groups enabling strong coordination within the enzyme’s active site via hydrogen bonding and ionic interactions (Steinrücken & Amrhein, 1980).

The inhibition is largely non-covalent but highly stable due to multi-point binding interactions involving magnesium-mediated coordination complexes. The resulting metabolic blockade prevents biosynthesis of phenylalanine, tyrosine, and tryptophan, leading to downstream disruption of protein synthesis and secondary metabolite production. Toxicity is therefore rooted in molecular mimicry and competitive enzyme inhibition rather than covalent modification.

3.5 Triazines (e.g. atrazine)

Triazine herbicides act through specific binding to the QB binding niche of the D1 protein within photosystem II. Structurally, the chlorinated s-triazine ring provides an electron-deficient aromatic system capable of stable hydrophobic and hydrogen-bonding interactions within the plastoquinone binding pocket (Fuerst & Norman, 1991).

By occupying this site, triazines prevent electron transfer from QA to QB, effectively blocking plastoquinone reduction. This interrupts the photosynthetic electron transport chain, inhibiting proton gradient formation across the thylakoid membrane and suppressing ATP synthesis. The

resulting electron leakage promotes formation of reactive oxygen species, which induce oxidative degradation of membrane lipids and proteins. Toxicity is thus a consequence of physical blockage of electron-transfer chemistry rather than enzymatic inhibition *per se*.

3.6 Organochlorines

Organochlorine pesticides are highly halogenated organic compounds whose biological activity is fundamentally governed by the strong electron-withdrawing effect of chlorine substituents, molecular lipophilicity, and conformational stability. Structurally, they include chlorinated aromatics (e.g., DDT), cyclodienes (e.g., aldrin, dieldrin), and hexachlorocyclohexane isomers (e.g., lindane), all characterised by extensive carbon–chlorine bonding that significantly reduces chemical reactivity towards hydrolysis and oxidation (ATSDR, 2002; Roberts & Hutson, 1999).

From a chemical perspective, the toxicity of organochlorines is not primarily due to covalent enzyme inhibition, as seen in organophosphates, but rather arises from strong hydrophobic partitioning into lipid membranes and selective binding to ion channel proteins within excitable tissues. Their high octanol–water partition coefficients (log Kow often > 4–6) reflect dominant dispersion forces and van der Waals interactions with phospholipid bilayers, leading to bioaccumulation in fatty tissues and prolonged biological half-lives (Evenset et al., 2023).

3.7 Interaction with neuronal ion channels

The principal mechanism of neurotoxicity involves disruption of ion channel kinetics, particularly voltage-gated sodium channels (Nav) and, in some subclasses, γ-aminobutyric acid ($GABA_A$) receptor–chloride channels. Organochlorines alter the conformational gating of these membrane proteins through non-covalent binding within hydrophobic channel domains.
For DDT and related diphenyl aliphatic compounds, the molecule stabilises the open state of sodium channels by interacting with hydrophobic amino acid residues lining the channel pore. This delays channel inactivation, prolonging sodium influx and causing repetitive neuronal firing and hyperexcitability (Narahashi, 2002). The effect is strongly influenced by molecular geometry; the para-para isomer of DDT exhibits significantly higher activity due to optimal spatial alignment with channel binding sites.

Cyclodiene organochlorines such as lindane and dieldrin act primarily as non-competitive antagonists of $GABA_A$ receptors. These compounds bind to the chloride channel complex at a site distinct from the GABA binding domain, reducing chloride ion flux into neurons. Since chloride influx is responsible for membrane hyperpolarisation, its inhibition leads to neuronal depolarisation and CNS excitation (Cole & Casida, 1986). This interaction is driven by hydrophobic forces and steric complementarity rather than ionic bonding.

4. Application Patterns and Case Studies in Nigeria

In commercial agricultural systems, pesticide and herbicide application patterns strongly influence the effective chemical dose reaching target organisms, as well as the subsequent environmental fate, transformation pathways, and exposure risks. From a chemistry perspective, frequency of application, formulation mixing, and operator practices directly affect solution-phase reactions, adsorption–desorption equilibria, and degradation kinetics in soil–plant–water systems.

4.1 Southwestern Nigeria (Vegetable Farming Systems)

Field studies conducted in Oyo and Ogun States provide a representative case of intensive pesticide use in peri-urban vegetable production systems, where pest pressure, short crop cycles, and limited agronomic extension services drive frequent chemical interventions (Bamidele et al., 2019; Adeyeye & Osibanjo, 2017).

4.1.1 High Application Frequency and Residue Accumulation

Reported practices indicate that approximately 68–75% of farmers apply pesticide sprays more than twice weekly during peak growing seasons. Chemically, such high application frequency reduces the time available for environmental dissipation processes such as hydrolysis, photolysis, and microbial biodegradation. As a result, successive applications can lead to quasi-steady-state accumulation of active ingredients and metabolites in foliar surfaces, soil matrices, and nearby aquatic systems.

In compounds with moderate persistence (e.g., organophosphates and pyrethroids), repeated dosing can maintain concentrations above degradation thresholds, effectively saturating adsorption sites on soil organic matter and clay minerals. This alters partition coefficients (Kd and Koc behaviour), increasing the likelihood of off-site transport via runoff or volatilisation, particularly under tropical rainfall conditions.

4.1.2 Limited use of personal protective equipment (PPE)

Only 20–30% of farmers report consistent use of PPE during pesticide handling and application. From a chemical exposure standpoint, this increases the probability of dermal absorption and inhalation of volatile or semi-volatile formulations, particularly emulsifiable concentrates and wettable powders containing organic solvents.

Many pesticide formulations contain adjuvants such as surfactants, xylene derivatives, and petroleum distillates, which enhance cuticular penetration by increasing membrane fluidity and disrupting lipid bilayers. Consequently, lack of PPE amplifies systemic

exposure by facilitating transdermal transport of lipophilic active ingredients, especially pyrethroids and chlorinated organics.

4.1.3 Tank mixing and chemical interaction phenomena

A particularly important chemical feature of pesticide use in Southwestern Nigerian vegetable systems is the common practice of tank mixing multiple pesticide formulations in a single spray solution. This practice introduces complex multi-component chemical systems where interactions may occur between active ingredients, solvents, and formulation additives (Green & Beestman, 2007; Knowles, 2008). From a chemical perspective, such mixtures can result in:

(a) **pH-driven degradation reactions:** Many pesticide-active ingredients are pH-sensitive. For example, organophosphates may undergo accelerated hydrolysis under alkaline conditions, producing oxon-derivatives or phosphoric acid esters with altered toxicity profiles (Racke, 1993; Ware & Whitacre, 2004).

(b) **Redox interactions:** Certain mixtures may facilitate oxidative transformation of susceptible compounds, particularly in the presence of metal ions (Fe^{3+}, Cu^{2+}) present in water or formulation impurities (Katagi, 2010; Fenner et al., 2013).

(c) **Solubility and partition effects:** Co-solvents and surfactants can alter the apparent solubility of hydrophobic compounds, increasing their bioavailability and potentially enhancing uptake by plant tissues and non-target organisms (Green & Beestman, 2007; Schwarzenbach et al., 2017).

(d) **Competitive adsorption and displacement:** In soil or spray droplets, structurally similar compounds may compete for adsorption sites, modifying mobility and leaching potential (Spark & Swift, 2002; Schwarzenbach et al., 2017).

Importantly, while most tank mixtures are intended to enhance efficacy, they may inadvertently promote the formation of transformation products with higher biological activity or different toxicological profiles than the parent compounds (Fenner et al., 2013; Katagi, 2010). This is particularly relevant for organophosphate and carbamate mixtures, where differential hydrolysis rates can lead to transient accumulation of more reactive intermediates (Racke, 1993).

4.1.4. Implications for Environmental Chemical Fate

The combined effect of high-frequency application, inadequate protective handling, and complex mixture chemistry results in a dynamic chemical environment characterised by:

(i) Increased steady-state concentrations of active ingredients in soil–water systems

(ii) Enhanced formation of secondary transformation products

(iii) Altered degradation kinetics due to formulation interactions

(iv) Increased potential for non-target exposure through volatilisation, runoff, and dermal contact pathways (Arias-Estévez et al., 2008; Fenner et al., 2013; Schwarzenbach et al., 2017).

In tropical agroecosystems such as those in Southwestern Nigeria, these processes are further intensified by elevated temperatures, high rainfall intensity, and high microbial activity, all of which influence hydrolysis rates, photodegradation pathways, and sorption–desorption equilibria.

4.1.5 Concluding chemical perspective

From a chemical standpoint, pesticide application patterns in Southwestern Nigerian vegetable farming systems represent coupled physico-chemical systems rather than isolated application events. High-frequency dosing, combined formulations, and limited exposure controls collectively modify reaction environments, influencing degradation pathways, molecular stability, and toxicological outcomes. The net effect is not only increased chemical load but also altered transformation chemistry, with implications for environmental persistence and human exposure risk.

4.2 Northern Nigeria (Irrigated Agriculture)

The irrigated agricultural zones of Northern Nigeria, particularly in Kano and Kaduna States, constitute some of the most intensive horticultural production areas in the country. Tomato (*Solanum lycopersicum*) and pepper (*Capsicum* spp.) cultivation in these regions is characterised by high pest pressure arising from continuous cropping, favourable climatic conditions for insect proliferation, and year-round irrigation practices. Consequently, insecticides are applied frequently to maintain marketable yields and minimise economic losses (Abubakar et al., 2018; Sosan et al., 2020).

From a chemical perspective, the intensive use of insecticides in irrigated farming systems significantly influences the environmental fate, transformation, and accumulation of pesticide residues in agricultural produce. Commonly used insecticides include organophosphates (e.g., chlorpyrifos and diazinon), carbamates (e.g., carbofuran), and pyrethroids (e.g., cypermethrin and lambda-cyhalothrin), all of which possess distinct physicochemical properties that determine their persistence and residue behaviour in crops (Casida & Durkin, 2013).

4.2.1 Residue Formation and Persistence in Vegetables

Pesticide residues in vegetables arise when the rate of

pesticide application exceeds the rate of degradation, metabolism, volatilisation, or wash-off from plant surfaces. Chemically, residue persistence is governed by factors such as molecular stability, photolytic susceptibility, hydrolysis kinetics, vapour pressure, and lipophilicity (Racke, 1993).

Many pyrethroids used in tomato and pepper production exhibit high octanol–water partition coefficients (log *K*ow > 4), promoting strong adsorption to the waxy cuticular layers of fruits and leaves. This hydrophobic interaction reduces immediate removal by irrigation water and rainfall, thereby increasing residue persistence until harvest (Richardson et al., 2019). Similarly, certain organophosphates undergo relatively slow degradation under field conditions, especially when repeated applications maintain residue concentrations above microbial degradation thresholds.

Studies conducted in Kano and Kaduna States have reported pesticide residue concentrations in vegetables that exceed European Union Maximum Residue Limits (EU MRLs) by two to five times in some market samples (Abubakar et al., 2018). Such exceedances suggest either excessive application rates, shortened pre-harvest intervals, repeated applications, or a combination of these factors.

4.2.2 Influence of Irrigation on Pesticide Behaviour

Irrigation practices substantially modify pesticide chemistry within agricultural systems. Frequent watering increases soil moisture content, which may enhance hydrolytic degradation of susceptible compounds such as carbamates and certain organophosphates. However, irrigation can also facilitate the redistribution of pesticides through surface runoff, infiltration, and transport into adjacent water bodies (Arias-Estévez et al., 2008).

In sandy alluvial soils common within many irrigated areas of Northern Nigeria, pesticides with relatively low sorption coefficients (*K*oc) may exhibit increased mobility. Compounds such as atrazine and some neonicotinoids are particularly susceptible to downward transport through the soil profile, increasing the potential for groundwater contamination. Conversely, highly lipophilic pyrethroids tend to remain associated with soil organic matter and suspended particulates, resulting in accumulation within sediments rather than aqueous phases.

4.2.3 Chemical Implications of Repeated Insecticide Applications

Repeated insecticide applications create conditions that favour residue accumulation and the formation of transformation products. Environmental processes such as oxidation, hydrolysis, photolysis, and microbial metabolism generate metabolites that may retain biological activity or exhibit distinct toxicological characteristics compared with parent compounds (Roberts & Hutson, 1999).

For example, chlorpyrifos may undergo oxidative desulfuration to produce chlorpyrifos-oxon, a metabolite with substantially greater acetylcholinesterase inhibitory activity than the parent pesticide. Similarly, pyrethroid degradation can yield intermediate compounds that remain biologically active in aquatic environments. Therefore, residue assessments based solely on parent compounds may underestimate total toxicological burden.

4.2.4 Implications for Food Safety and Environmental Chemistry

The detection of pesticide residues above EU MRLs in tomatoes and peppers has important implications for food safety and environmental quality. Maximum Residue Limits are established on the basis of toxicological evaluation, dietary exposure modelling, and acceptable daily intake thresholds. Exceedance of these limits indicates that degradation and dissipation processes are insufficient to reduce residue concentrations to internationally accepted levels before consumption (European Food Safety Authority [EFSA], 2023).

From a chemical perspective, residue accumulation reflects an imbalance between pesticide input and environmental transformation processes. The combination of frequent insecticide applications, high cropping intensity, and irrigation-driven transport mechanisms contributes to the persistence of pesticide residues within the agricultural production chain.

4.2.5 Concluding Chemical Perspective

The irrigated agricultural systems of Kano and Kaduna States exemplify how intensive pesticide use can influence residue dynamics through interactions among molecular properties, environmental conditions, and agronomic practices. High insecticide usage in tomato and pepper farming promotes residue accumulation when application frequencies exceed degradation rates. Consequently, pesticide concentrations in vegetables may surpass regulatory limits, highlighting the importance of understanding pesticide chemistry, degradation kinetics, and residue behaviour in ensuring both agricultural productivity and food safety.

4.3 Cocoa Production Belt (Southwest Forest Zone)

The cocoa-producing regions of Southwestern Nigeria, particularly in Ondo, Osun, Ogun, Oyo, and Ekiti States, constitute one of the most chemically intensive agricultural zones in the country. The perennial nature of cocoa cultivation, coupled with persistent insect pest infestations and fungal diseases such as black pod disease caused by *Phytophthora* species, has resulted in extensive reliance on organophosphate insecticides and fungicides for crop protection (Aikpokpodion et al., 2012; Oluyole & Sanusi, 2009).

From a chemistry perspective, the application patterns observed in cocoa plantations significantly influence pesticide fate, transformation pathways, residue accumulation, and long-term soil chemistry. The

repeated introduction of bioactive compounds into relatively stable plantation ecosystems creates conditions conducive to the accumulation of both parent compounds and degradation products within soil and sediment matrices.

4.3.1 Application Practices and Chemical Dispersion

Pesticides in cocoa plantations are commonly applied through knapsack sprayers and, in some large-scale operations, aerial spraying programmes. These application methods affect droplet size distribution, volatilisation dynamics, and deposition efficiency. Aerial spraying typically produces finer droplets with greater surface-area-to-volume ratios, increasing the likelihood of spray drift and atmospheric transport, while knapsack spraying often results in localised accumulation due to repeated treatment of the same canopy zones (Matthews et al., 2014).

Organophosphate insecticides such as chlorpyrifos and diazinon are frequently employed to control mirids and other cocoa pests. These compounds contain electrophilic phosphorus centres that are susceptible to hydrolysis; however, repeated application can exceed environmental degradation capacity, resulting in the persistence of measurable residues within plantation soils (Racke, 1993). Fungicides commonly used in cocoa systems, including copper-based formulations and synthetic organic fungicides, further contribute to the chemical burden of plantation environments through continuous seasonal application.

4.3.2 Soil Retention and Accumulation Processes

The forest soils of Southwestern Nigeria are generally characterised by relatively high organic matter contents and significant clay fractions. These properties strongly influence pesticide sorption through hydrophobic partitioning, ion exchange interactions, and surface complexation mechanisms (Spark & Swift, 2002).

Many organophosphate insecticides exhibit moderate to high affinity for soil organic matter, while pyrethroid and certain fungicide residues display even stronger adsorption due to their elevated lipophilicity. Sorption reduces immediate mobility but simultaneously promotes long-term retention within soil horizons. Over successive years of application, residual concentrations may accumulate in soils, particularly where degradation rates are insufficient to offset annual chemical inputs.

Copper-containing fungicides present a unique case because copper is an elemental contaminant that cannot be degraded chemically or biologically. Instead, repeated fungicide applications increase total soil copper concentrations through progressive accumulation. Copper ions may subsequently interact with clay minerals, humic substances, and soil colloids through complexation and adsorption processes, altering soil geochemistry and potentially affecting microbial activity and nutrient cycling (Komárek et al., 2010).

4.3.3 Transformation and Persistence of Agrochemicals

Environmental transformation of pesticides within cocoa plantations occurs through hydrolysis, photolysis, oxidation, reduction, and microbial metabolism. However, the dense cocoa canopy characteristic of forest-zone plantations often limits direct solar irradiation reaching the soil surface, reducing photodegradation rates relative to open-field agricultural systems (Arias-Estévez et al., 2008).

Under these conditions, microbial degradation becomes the dominant transformation pathway. Nevertheless, repeated pesticide inputs may maintain residue concentrations above degradation thresholds, resulting in pseudo-persistence, whereby compounds continue to be detected despite relatively short intrinsic half-lives. Furthermore, some degradation products may retain toxicological significance. For example, oxidative transformation of chlorpyrifos can produce chlorpyrifos-oxon, a metabolite exhibiting greater acetylcholinesterase inhibitory activity than the parent compound (Racke, 1993).

4.3.4 Evidence of Long-Term Soil Contamination

Several investigations within cocoa-producing regions of Nigeria have reported detectable concentrations of pesticide residues in plantation soils years after repeated applications (Aikpokpodion et al., 2012; Ogbeide et al., 2016). From a chemical perspective, such findings reflect the cumulative effects of sorption, slow degradation kinetics, and repeated agrochemical inputs.

Long-term contamination may alter soil physicochemical properties through interactions between pesticide residues and soil organic matter. Persistent residues can affect microbial enzymatic activity, modify nutrient cycling processes, and influence the redox chemistry of soil systems. In the case of metal-based fungicides, accumulation may additionally affect cation exchange processes and trace element bioavailability.

4.3.5 Implications for Environmental Chemistry

The cocoa plantation ecosystem represents a semi-closed environmental compartment in which agrochemicals are repeatedly introduced into relatively stable soil–plant systems. Consequently, long-term environmental behaviour is governed less by individual application events and more by cumulative chemical loading. The balance between annual pesticide inputs and degradation processes determines whether residues dissipate or progressively accumulate within plantation soils.

From a chemical standpoint, the persistence observed in cocoa-growing regions arises from the interaction of

several factors, including strong sorption to organic matter, reduced photolytic degradation under dense canopy cover, repeated applications, and the intrinsic stability of certain pesticide classes and fungicide constituents. These processes collectively contribute to the long-term contamination patterns documented in several cocoa-producing areas of Southwestern Nigeria.

5. Environmental Fate and Chemical Behaviour

5.1 Chemical Behaviour in Nigerian Agroecosystems

The environmental fate of pesticides in Nigerian agroecosystems is strongly influenced by tropical climatic conditions, including elevated temperatures, intense ultraviolet radiation, and high rainfall variability. These factors accelerate abiotic and biotic transformation processes such as hydrolysis, photolysis, and microbial degradation (Akan et al., 2013).

Hydrolysis rates are enhanced in warm, moist soils, particularly for ester-containing compounds such as carbamates and pyrethroids. Photolytic degradation is significant for surface-applied pesticides with conjugated aromatic systems, while sorption dynamics are strongly influenced by clay-rich and organic matter–rich soils typical of many agricultural regions (Oluwole et al., 2015). Runoff during heavy rainfall events contributes significantly to pesticide transport into adjacent aquatic systems, where residues have been frequently detected.

From a mechanistic standpoint, herbicides used in Nigerian agriculture span distinct chemical classes with fundamentally different modes of action: EPSPS inhibition (glyphosate), photosystem II disruption (atrazine), and auxin mimicry (2,4-D). Despite these differences, their environmental fate is governed by shared physicochemical parameters, particularly ionisation behaviour, sorption affinity, and degradation kinetics under tropical climatic conditions.

In Nigeria, high rainfall intensity, elevated temperatures, and heterogeneous soil compositions collectively modulate herbicide transport and transformation. As a result, even compounds with strong soil-binding characteristics, such as glyphosate, can be mobilised into aquatic systems, while moderately persistent compounds like atrazine exhibit enhanced leaching risk. The overall chemical profile of herbicide use therefore reflects a balance between molecular stability, environmental reactivity, and agroecosystem dynamics rather than intrinsic toxicity alone.

5.2 Summary of Chemical Trends in Nigeria

Pesticide usage in Nigeria reflects a structural transition from highly persistent organochlorines towards more chemically reactive organophosphates, carbamates, pyrethroids, and emerging neonicotinoids. However, this transition has shifted the toxicological profile from chronic environmental persistence to acute, mechanism-driven toxicity.

The dominant chemical determinants of toxicity include electrophilic phosphorus centres in organophosphates, reversible carbamylation in carbamates, lipophilicity-driven bioaccumulation in pyrethroids, and high-affinity receptor binding in neonicotinoids. These mechanisms collectively define current exposure risks in agricultural systems.

6. Analytical Chemistry and Residue Monitoring

The increasing use of pesticides and herbicides in commercial agriculture has necessitated the development of highly sensitive and selective analytical techniques for the detection, quantification, and monitoring of agrochemical residues in environmental and food matrices. From an analytical chemistry perspective, residue monitoring involves the extraction, separation, identification, and quantification of trace concentrations of pesticide active ingredients and their metabolites in complex matrices such as soil, water, crops, sediments, and biological tissues (Anastassiades et al., 2003; Alder et al., 2006).

The effectiveness of residue monitoring depends largely on the physicochemical properties of the target compounds, including polarity, volatility, thermal stability, molecular mass, and ionisation behaviour. Consequently, modern pesticide analysis relies on a combination of chromatographic separation techniques and advanced mass spectrometric detection systems capable of achieving detection limits in the μg kg^{-1} to ng kg^{-1} range.

6.1 Analytical Instruments for Pesticide and Herbicide Analysis

6.1.1 Gas Chromatography–Mass Spectrometry (GC–MS)

Gas chromatography coupled with mass spectrometry (GC–MS) remains one of the most widely employed techniques for the analysis of volatile and semi-volatile pesticide residues. The technique is particularly suitable for organochlorine pesticides, pyrethroids, and several organophosphate compounds due to their relatively low polarity, thermal stability, and volatility after sample preparation (Wilkowska & Biziuk., 2011). In GC–MS analysis, compounds are separated according to their vapour pressures and interactions with the stationary phase of the chromatographic column. Following separation, molecules undergo ionisation, typically by electron ionisation (EI), producing characteristic fragmentation patterns that facilitate structural identification. The resulting mass spectra provide both qualitative and quantitative information, enabling accurate determination of pesticide residues even in highly complex environmental samples.

For organochlorines such as DDT, aldrin, and lindane, GC–MS offers excellent sensitivity because these compounds possess high thermal stability and generate

distinctive chlorine isotope fragmentation patterns. Similarly, pyrethroids such as cypermethrin and permethrin are routinely analysed using GC–MS owing to their hydrophobic character and favourable chromatographic behaviour (Lehotay et al., 2010).

6.1.2 Liquid Chromatography–Tandem Mass Spectrometry (LC–MS/MS)

Many modern herbicides and pesticides exhibit high polarity, low volatility, and thermal instability, making them unsuitable for gas chromatographic analysis. In such cases, liquid chromatography–tandem mass spectrometry (LC–MS/MS) has become the analytical method of choice.

Glyphosate, aminomethylphosphonic acid (AMPA), paraquat, and other polar herbicides are particularly amenable to LC–MS/MS because they remain stable in solution and can be separated without prior derivatisation. The technique combines high-performance liquid chromatography (HPLC) with tandem mass spectrometric detection, allowing selective monitoring of precursor-to-product ion transitions through multiple reaction monitoring (MRM) modes (Hernández et al., 2013).

From a chemical perspective, LC–MS/MS exploits differences in polarity, molecular mass, and ionisation efficiency. Electrospray ionisation (ESI) is commonly used for glyphosate analysis because the phosphonate and carboxylate groups readily form charged species in solution. This provides exceptional sensitivity and selectivity, often achieving detection limits below regulatory maximum residue limits (MRLs).

6.1.3 QuEChERS Extraction and Multi-Residue Screening

One of the most significant advances in pesticide residue analysis has been the development of the QuEChERS method, an acronym for *Quick, Easy, Cheap, Effective, Rugged, and Safe* (Anastassiades et al., 2003).

QuEChERS is designed as a universal sample preparation technique capable of extracting a broad range of pesticide classes from fruits, vegetables, soils, and other agricultural products. The method typically involves extraction with acetonitrile followed by partitioning using magnesium sulfate and buffering salts. Subsequent dispersive solid-phase extraction (d-SPE) removes interfering matrix components such as pigments, lipids, sugars, and organic acids.

Chemically, the success of QuEChERS arises from selective partitioning of pesticide molecules between aqueous and organic phases based on polarity and solubility differences. The approach allows simultaneous recovery of compounds with diverse physicochemical properties, making it particularly suitable for multi-residue screening programmes in agricultural monitoring laboratories (Lehotay et al., 2010).

When combined with GC–MS or LC–MS/MS, QuEChERS enables the simultaneous determination of hundreds of pesticide residues within a single analytical workflow, significantly improving laboratory efficiency and analytical throughput.

6.2 Challenges in Residue Monitoring in Nigeria

Despite advances in analytical chemistry, routine pesticide residue monitoring in Nigeria remains limited. Several factors constrain the implementation of comprehensive surveillance programmes.

6.2.1 Limited Analytical Infrastructure

The availability of well-equipped analytical laboratories remains a major challenge. Advanced instruments such as GC–MS/MS, LC–MS/MS, and high-resolution mass spectrometers require substantial capital investment, specialised maintenance, and highly trained personnel. Consequently, analytical capacity is concentrated within a small number of research institutions and regulatory agencies (FAO & WHO, 2019).

6.2.2 High Cost of Analytical Standards

Accurate pesticide quantification requires certified reference materials and analytical standards of high purity. These standards are often expensive and must be regularly replenished to maintain calibration accuracy and quality assurance protocols. The financial burden associated with acquiring standards for hundreds of pesticide active ingredients significantly limits routine monitoring programmes in many developing countries.

From a chemical metrology perspective, the absence of appropriate standards compromises analytical accuracy, precision, and inter-laboratory comparability, reducing confidence in residue data.

6.2.3 Inconsistent Regulatory Enforcement

Effective residue monitoring requires a coordinated framework linking analytical laboratories, agricultural extension services, food safety agencies, and environmental regulators. In Nigeria, inconsistent enforcement of pesticide regulations often limits the frequency and scope of monitoring activities (Federal Ministry of Agriculture and Rural Development [FMARD], 2021).

As a result, pesticide residues in agricultural commodities may remain undetected, and compliance with established maximum residue limits may not be consistently verified. This challenge is particularly important for export-oriented crops where international markets increasingly require rigorous residue certification.

6.3 Concluding Chemical Perspective

Analytical chemistry forms the foundation of pesticide and herbicide residue monitoring by providing the tools necessary to identify and quantify trace agrochemical contaminants in complex environmental

and food matrices. Modern techniques such as GC–MS, LC–MS/MS, and QuEChERS-based multi-residue analysis offer exceptional sensitivity, selectivity, and throughput, enabling comprehensive assessment of pesticide occurrence and environmental fate. However, in Nigeria, limitations in laboratory infrastructure, analytical standards, and regulatory implementation continue to constrain routine monitoring efforts. Strengthening analytical capacity is therefore essential for improving food safety, environmental protection, and sustainable agricultural management.

7. Toxicological Chemistry and Human Exposure

The extensive use of pesticides and herbicides in commercial agriculture in Nigeria has raised significant concerns regarding human exposure and associated toxicological effects. From a toxicological chemistry perspective, adverse health outcomes are fundamentally linked to the molecular structure, physicochemical properties, metabolic transformation, and biochemical reactivity of agrochemicals. The interaction of these compounds with biological macromolecules, cellular membranes, and enzymatic systems determines both the magnitude and duration of toxic effects (Casida & Durkin, 2013).

Human exposure occurs through multiple pathways, with occupational exposure among farmers and pesticide applicators representing the most significant route in agricultural communities. The extent of exposure depends on application practices, formulation type, environmental conditions, and the use of personal protective equipment.

7.1 Toxicological Implications of Pesticide and Herbicide Application in Nigerian Environment

7.1.1 Dermal Absorption During Spraying

Dermal absorption is the primary route of pesticide exposure among farmers involved in pesticide mixing, loading, and spraying operations. From a chemical standpoint, the ability of a pesticide to penetrate the skin is governed by its molecular size, lipophilicity, polarity, and formulation characteristics (Nielsen et al., 2007).

Many commonly used insecticides in Nigeria, particularly pyrethroids and organophosphates, possess sufficient lipophilicity to partition into the lipid-rich stratum corneum. Formulation additives such as surfactants, emulsifiers, and organic solvents can further enhance dermal permeability by disrupting skin barrier integrity and increasing solubilisation of active ingredients. Once absorbed, pesticides enter systemic circulation and undergo biotransformation primarily in the liver through cytochrome P450-mediated oxidation, hydrolysis, and conjugation reactions.

Repeated dermal exposure can result in cumulative body burdens, particularly where application frequencies are high and protective clothing is not routinely used.

7.1.2 Inhalation of Aerosolised Droplets

Inhalation represents another significant exposure pathway during pesticide application. Fine droplets generated during spraying may remain suspended in the atmosphere and be deposited within the respiratory tract depending on particle size distribution.

Chemically, inhalation exposure is particularly important for volatile and semi-volatile compounds. Following deposition in pulmonary tissues, pesticides may rapidly diffuse across the alveolar membrane due to the large surface area and extensive vascularisation of the lungs. The absorption kinetics of inhaled pesticides are often faster than those associated with dermal exposure, leading to rapid systemic distribution (Costa, 2018).

The risk of inhalation exposure increases during aerial spraying operations, application under windy conditions, and use of poorly calibrated spraying equipment that generates excessive aerosol formation.

7.1.3 Dietary Intake of Contaminated Produce

Dietary exposure occurs through consumption of food containing pesticide residues that remain following agricultural application. The persistence of residues depends on chemical stability, degradation kinetics, plant metabolism, and adherence to recommended pre-harvest intervals.

From a chemistry perspective, residue bioavailability is influenced by factors such as solubility, molecular polarity, and gastrointestinal absorption characteristics. Lipophilic compounds may partition into dietary fats and exhibit enhanced absorption across intestinal membranes, whereas highly polar compounds may follow alternative transport pathways (WHO, 2020).

In regions where pesticide application rates exceed recommended levels or residue monitoring is inadequate, dietary exposure may become a substantial contributor to chronic pesticide intake.

7.1.4 Oxidative Stress and Redox Imbalance

One of the most widely recognised biochemical consequences of pesticide exposure is oxidative stress. Many pesticides induce excessive production of reactive oxygen species (ROS), including superoxide radicals ($O_2^{\bullet -}$), hydroxyl radicals ($\bullet OH$), and hydrogen peroxide (H_2O_2), overwhelming endogenous antioxidant defence systems (Rani et al., 2021).

Chemically, ROS generation may occur through mitochondrial electron transport disruption, redox cycling reactions, or metabolic activation of pesticide molecules. Elevated ROS concentrations promote oxidative damage to cellular lipids, proteins, and nucleic acids.

Lipid peroxidation is particularly significant because polyunsaturated fatty acids within cellular membranes are highly susceptible to radical attack. This process generates secondary oxidation products such as malondialdehyde (MDA), which are frequently used as

biomarkers of pesticide-induced oxidative damage. Simultaneously, intracellular glutathione (GSH), a major cellular antioxidant, is depleted through detoxification reactions and direct ROS scavenging, reducing cellular resistance to oxidative injury (Abdollahi et al., 2004).

7.1.5 Inhibition of Cholinesterase Enzymes

The inhibition of cholinesterase enzymes remains one of the most important mechanisms of toxicity associated with organophosphate and carbamate insecticides.

Organophosphates contain electrophilic phosphorus centres capable of phosphorylating the active-site serine residue of acetylcholinesterase (AChE), forming stable phosphoester complexes that prevent enzymatic hydrolysis of acetylcholine (Sogorb & Vilanova, 2002). Carbamates produce a similar effect through reversible carbamylation of the enzyme.

The resulting accumulation of acetylcholine at cholinergic synapses leads to continuous stimulation of muscarinic and nicotinic receptors, producing a range of neurological effects including muscle fasciculation, respiratory distress, and neuromuscular dysfunction.

Biomonitoring studies in Nigerian farming communities have reported significantly reduced blood cholinesterase activity among pesticide applicators compared with unexposed control populations, indicating chronic occupational exposure to cholinesterase-inhibiting pesticides (Ogunjimi et al., 2020).

7.1.6 Endocrine Disruption and Hormonal Effects

Several pesticide classes have been implicated in endocrine disruption through interactions with hormone receptors, steroidogenic enzymes, and hormone transport proteins. Unlike acute neurotoxicity, endocrine effects often occur through subtle molecular interactions at relatively low exposure levels.

Chemically, some pesticides exhibit structural features that enable them to mimic endogenous hormones or interfere with receptor-mediated signalling pathways. Organochlorines and certain triazine herbicides have been shown to alter oestrogenic, androgenic, and thyroid hormone pathways through receptor binding or modification of hormone synthesis enzymes (Mnif et al., 2011).

Disruption of endocrine homeostasis may affect reproductive physiology, fertility, foetal development, and endocrine-regulated metabolic processes. These effects are often associated with chronic exposure and may involve complex interactions between parent compounds and biologically active metabolites.

7.2 Biomonitoring Evidence from Nigerian Agricultural Communities

Studies conducted among pesticide applicators in Nigeria have demonstrated biochemical evidence of pesticide exposure, including reduced cholinesterase activity, elevated oxidative stress biomarkers, and altered antioxidant enzyme profiles (Ogunjimi et al., 2020; Akinola et al., 2019).

From a toxicological chemistry perspective, these findings are consistent with the known molecular mechanisms of commonly used pesticides, particularly organophosphates and carbamates. The observed biochemical alterations reflect direct interactions between reactive pesticide molecules and critical biological targets, including enzymes, membrane lipids, and cellular antioxidant systems.

7.3 Chemical Perspective Summary

The toxicological effects of pesticides and herbicides in Nigerian commercial agriculture are fundamentally rooted in molecular-level interactions between agrochemicals and biological systems. Dermal absorption, inhalation, and dietary intake facilitate systemic exposure, while toxic effects arise through oxidative stress induction, cholinesterase inhibition, endocrine disruption, and related biochemical mechanisms. The strong association between pesticide exposure and altered biomarker profiles among Nigerian farmers highlights the importance of understanding the chemistry of pesticide absorption, metabolism, and toxicity in developing effective exposure mitigation strategies and improving occupational health outcomes.

8. Health Risk Implications

The widespread application of pesticides and herbicides in Nigerian agriculture has generated increasing concern regarding their implications for human health. From a toxicological chemistry perspective, health risks arise from the interaction of agrochemical molecules and their metabolites with biological macromolecules, including enzymes, receptors, nucleic acids, and cellular membranes. The severity of adverse effects depends on factors such as chemical structure, dose, duration of exposure, metabolic activation, bioaccumulation potential, and individual susceptibility (Casida & Durkin, 2013; World Health Organization [WHO], 2020).

In Nigeria, occupational exposure among farmers and pesticide applicators, together with environmental and dietary exposure among rural communities, has been associated with a range of acute and chronic health outcomes. These effects reflect the diverse mechanisms through which pesticides and herbicides disrupt normal biochemical and physiological processes.

8.1 Health Effects of Pesticide and Herbicide Application in Nigerian Agricultural Farmlands

8.1.1 Acute Pesticide Poisoning

Acute pesticide poisoning remains one of the most frequently reported health consequences of pesticide exposure in developing agricultural systems. Symptoms commonly include headache, dizziness, nausea, vomiting, excessive sweating, respiratory distress, muscle weakness, and impaired coordination (WHO, 2020).

From a chemical perspective, acute toxicity is often associated with rapid inhibition of essential enzymes or disruption of neuronal signalling pathways. Organophosphate and carbamate insecticides, for example, inhibit acetylcholinesterase through phosphorylation or carbamylation of the active-site serine residue, resulting in excessive accumulation of acetylcholine at cholinergic synapses (Sogorb & Vilanova, 2002). This produces continuous stimulation of muscarinic and nicotinic receptors, leading to the characteristic symptoms of cholinergic toxicity.

Pyrethroid insecticides may similarly induce acute neurotoxic effects through alteration of voltage-gated sodium channel kinetics, causing repetitive neuronal firing and sensory disturbances. The likelihood of acute poisoning is often increased by inadequate use of personal protective equipment, improper handling practices, and accidental overexposure during pesticide application.

8.1.2 Neurological Disorders Associated with Chronic Organophosphate Exposure

Chronic exposure to organophosphate pesticides has been associated with long-term neurological impairment in occupationally exposed populations. Unlike acute toxicity, which results from immediate cholinesterase inhibition, chronic effects involve more complex biochemical pathways, including oxidative stress, neuroinflammation, mitochondrial dysfunction, and altered neurotransmitter regulation (Costa, 2018).

Chemically, organophosphates and their oxon metabolites can interact with a range of neuronal proteins beyond acetylcholinesterase, including neuropathy target esterase (NTE) and various serine hydrolases. Persistent disruption of these biochemical systems may contribute to neurodegenerative processes, cognitive impairment, memory deficits, and peripheral neuropathies (Jokanović, 2018).

Several epidemiological studies have reported associations between long-term occupational exposure to organophosphates and increased risks of neurological disorders, particularly among agricultural workers with repeated exposure over many years.

8.1.3 Potential Carcinogenic Risks Associated with Herbicide Exposure

The potential carcinogenicity of certain herbicides has attracted considerable scientific and regulatory attention. Carcinogenic risk is generally linked to mechanisms such as oxidative DNA damage, chromosomal instability, endocrine disruption, epigenetic modification, and prolonged cellular proliferation following chemical exposure (Guyton et al., 2015).

Glyphosate-based herbicides have been extensively studied because of their widespread agricultural use. Although regulatory agencies differ in their evaluations, some evidence suggests that prolonged exposure may contribute to increased risks of certain cancers through indirect mechanisms involving oxidative stress and genotoxicity (Guyton et al., 2015). Similarly, triazine herbicides such as atrazine have been investigated for their potential endocrine-mediated carcinogenic effects due to their ability to alter hormone-regulated cellular pathways.

From a chemical standpoint, carcinogenic potential is often determined not only by the parent compound but also by reactive metabolites generated during biotransformation. These metabolites may interact with DNA, proteins, or cellular signalling systems, increasing the likelihood of mutagenic or tumour-promoting effects.

8.1.4 Developmental Toxicity in Children

Children are particularly vulnerable to pesticide exposure because of their developing physiological systems, higher intake of food and water relative to body mass, and immature detoxification mechanisms. Exposure may occur through consumption of contaminated food, ingestion of contaminated water, inhalation of pesticide drift, or contact with contaminated soils and household surfaces (United Nations Children's Fund [UNICEF], 2021).

From a toxicological chemistry perspective, developmental toxicity arises when agrochemicals interfere with critical biochemical processes involved in growth, neurodevelopment, and endocrine regulation. Certain pesticides can cross the placental barrier or be transferred through breast milk, exposing the developing foetus or infant during sensitive periods of development (Mnif et al., 2011).

Mechanistically, developmental effects may result from oxidative stress, endocrine disruption, altered neurotransmitter signalling, or interference with gene expression pathways regulating organogenesis. Such disruptions have been associated with adverse outcomes including reduced cognitive performance, behavioural abnormalities, impaired growth, and developmental delays.

8.1.5 Disproportionate Impact on Rural Communities

Rural populations in Nigeria experience a disproportionate burden of pesticide-related health risks. Several factors contribute to this increased vulnerability, including frequent occupational

exposure, limited access to healthcare services, inadequate training in pesticide handling, and low awareness of chemical safety practices (Food and Agriculture Organization [FAO] & WHO, 2014).

From an exposure science perspective, repeated low-level exposure can lead to cumulative toxicological effects, particularly when environmental monitoring and medical surveillance are limited. In many farming communities, improper storage of pesticides, reuse of pesticide containers, and failure to observe recommended pre-harvest intervals further increase the likelihood of exposure among both agricultural workers and the wider population.

Moreover, limited healthcare access often delays diagnosis and treatment of pesticide-related illnesses, increasing the severity of both acute and chronic health outcomes. Consequently, the public health burden associated with pesticide exposure is often greater in rural agricultural regions than in urban populations.

8.2 Health Perspective Summary

The health risks associated with pesticide and herbicide application in Nigerian agricultural fields are fundamentally linked to the chemical properties and biological reactivity of these compounds. Acute poisoning results primarily from enzyme inhibition and neurochemical disruption, while chronic exposure may contribute to neurological disorders, carcinogenic processes, endocrine dysfunction, and developmental toxicity. The persistence of these risks is amplified in rural communities where occupational exposure is common and access to healthcare and chemical safety information remains limited. Understanding the chemistry underlying pesticide toxicity is therefore essential for improving risk assessment, exposure management, and public health protection within Nigerian agricultural systems.

9. Challenges in Agrochemical Management in Nigeria

The effective management of agrochemicals remains a major challenge within Nigeria's agricultural sector despite the increasing reliance on pesticides and herbicides for crop protection and productivity enhancement. From a chemical and environmental management perspective, agrochemical stewardship encompasses the regulation, distribution, storage, application, monitoring, and disposal of pesticide products throughout their life cycle. Deficiencies at any stage of this process can significantly influence environmental fate, residue accumulation, human exposure, and ecological toxicity (Food and Agriculture Organization [FAO] & World Health Organization [WHO], 2014).

In Nigeria, several interconnected challenges undermine the safe and sustainable use of agrochemicals. These include weak regulatory enforcement, the circulation of counterfeit pesticide products, low adoption of Integrated Pest Management (IPM), inadequate storage infrastructure, insufficient farmer training, and limited residue monitoring capacity. Collectively, these factors contribute to increased chemical exposure risks and environmental contamination.

9.1 Weak Regulatory Enforcement

One of the most significant barriers to effective agrochemical management in Nigeria is inconsistent regulatory enforcement. Although pesticide registration and regulation are overseen by relevant government agencies, implementation and monitoring activities are often constrained by inadequate funding, limited technical capacity, and insufficient field inspection programmes (FAO & WHO, 2014).

From a chemical safety perspective, weak enforcement may allow the continued use of obsolete, highly hazardous, or unregistered pesticide formulations. Such products may possess unfavourable toxicological profiles, prolonged environmental persistence, or unacceptable residue characteristics. Inadequate regulatory oversight can also hinder compliance with recommended application rates, pre-harvest intervals, and environmental protection measures, thereby increasing the likelihood of residue accumulation in food and environmental matrices.

Furthermore, insufficient post-registration surveillance limits the ability to assess environmental concentrations, degradation products, and long-term contamination trends, reducing the effectiveness of risk management strategies.

9.2 Circulation of Counterfeit and Substandard Pesticides

The widespread availability of counterfeit, adulterated, and substandard pesticide products represents a major chemical management challenge in Nigeria. Counterfeit agrochemicals may contain incorrect active ingredient concentrations, undeclared contaminants, inappropriate solvents, or entirely different chemical substances from those specified on product labels (Williamson et al., 2008).

From an analytical chemistry perspective, variations in formulation composition can significantly alter pesticide efficacy, degradation kinetics, toxicity, and environmental behaviour. Substandard products may contain excessive concentrations of active ingredients, resulting in phytotoxicity, elevated residue levels, and increased occupational exposure. Conversely, under-formulated products may encourage repeated applications, thereby increasing overall chemical loading within agricultural ecosystems.

The presence of formulation impurities may further contribute to unforeseen toxicological effects, particularly when contaminants possess greater persistence or toxicity than the intended active ingredients.

9.3 Low Adoption of Integrated Pest Management (IPM)

Integrated Pest Management (IPM) is a scientifically based pest control strategy that combines biological, cultural, mechanical, and chemical approaches to minimise pesticide reliance. However, adoption of IPM practices remains relatively low in many Nigerian agricultural systems (Pretty & Bharucha, 2015).

From a chemistry perspective, excessive dependence on synthetic pesticides increases cumulative environmental concentrations and promotes repeated exposure of pests to the same active ingredients. Such practices accelerate the development of pesticide resistance through selective pressure, often necessitating higher application rates or the introduction of more potent compounds.

The limited integration of non-chemical pest management approaches therefore contributes to increased agrochemical consumption and greater environmental contamination. In addition, repeated applications can alter degradation dynamics and promote the accumulation of both parent compounds and transformation products within soils, crops, and water bodies.

9.4 Poor Storage and Handling Infrastructure

Proper storage and handling are critical components of agrochemical management because many pesticides undergo physicochemical changes when exposed to unsuitable environmental conditions. In many rural areas of Nigeria, pesticides are frequently stored in residential buildings, farm sheds, or poorly ventilated structures lacking adequate temperature and humidity control (WHO, 2020).

Exposure to elevated temperatures, moisture, and direct sunlight can accelerate chemical degradation through hydrolysis, oxidation, photolysis, and volatilisation. Such processes may reduce product efficacy or generate degradation products with altered toxicological properties. For example, certain organophosphates may undergo oxidative transformation to oxon metabolites that exhibit greater acetylcholinesterase inhibitory activity than the parent compounds (Racke, 1993).

Improper storage also increases the risk of accidental exposure, contamination of food supplies, and environmental release through leakage or container deterioration.

9.5 Limited Farmer Training on Chemical Safety

The safe use of pesticides requires a sound understanding of formulation characteristics, dosage calculations, application techniques, personal protective equipment requirements, and disposal procedures. However, many farmers in Nigeria have limited access to formal training on pesticide safety and agrochemical stewardship (Ajayi & Akinnifesi, 2007).

From a chemical risk perspective, inadequate training often results in over-application, incorrect dilution ratios, inappropriate tank mixing, and failure to observe recommended re-entry or pre-harvest intervals. Such practices may alter the intended chemical behaviour of formulations and increase both occupational and environmental exposure.

For instance, indiscriminate mixing of multiple pesticides in a single spray tank may modify solution pH, promote hydrolytic degradation, or generate antagonistic and synergistic interactions among active ingredients. These changes can influence both efficacy and toxicity in ways that are difficult to predict without adequate chemical knowledge.

9.6 Inadequate Residue Surveillance Systems

Effective agrochemical management depends on routine monitoring of pesticide residues in food products, soils, water bodies, and biological samples. However, residue surveillance systems in Nigeria remain limited due to insufficient analytical infrastructure, inadequate funding, and shortages of trained personnel (FAO & WHO, 2019).

From an analytical chemistry perspective, comprehensive residue monitoring requires sophisticated instrumentation such as gas chromatography–mass spectrometry (GC–MS), liquid chromatography–tandem mass spectrometry (LC–MS/MS), and validated multi-residue analytical methods. The limited availability of such facilities restricts the capacity to detect and quantify pesticide residues at concentrations relevant to food safety and environmental protection.

Consequently, contamination events may remain undetected, and regulatory agencies may lack the data necessary to evaluate exposure trends, assess compliance with maximum residue limits (MRLs), or identify emerging contamination issues.

9.7 Implications for Human Health and Environmental Quality

The cumulative effect of these management challenges is an increased likelihood of pesticide misuse, environmental contamination, and human exposure. Weak regulatory systems, inadequate monitoring, and poor chemical stewardship facilitate the persistence of hazardous compounds within agricultural landscapes, resulting in contamination of soils, surface waters, groundwater resources, and agricultural produce.

From a toxicological chemistry standpoint, repeated exposure to pesticide residues can promote oxidative stress, endocrine disruption, neurotoxicity, and other adverse health outcomes. Simultaneously, environmental contamination may affect non-target organisms through bioaccumulation, biomagnification, and disruption of ecological processes.

Generally, the challenges facing agrochemical

management in Nigeria are closely linked to the chemistry of pesticide production, application, environmental fate, and toxicological behaviour. Weak regulatory enforcement, counterfeit pesticide circulation, limited adoption of IPM, poor storage infrastructure, inadequate farmer training, and insufficient residue surveillance collectively compromise the safe use of agrochemicals. Addressing these challenges requires strengthening regulatory frameworks, expanding analytical monitoring capacity, improving farmer education, and promoting sustainable pest management strategies capable of reducing both chemical exposure and environmental contamination.

10. Prospects for Sustainable Chemical Use

The future of agrochemical management in Nigeria will depend on the integration of advances in chemistry, toxicology, analytical science, biotechnology, and agricultural engineering to improve crop productivity while minimising risks to human health and the environment. From a chemical perspective, sustainable agricultural development requires a transition from heavy reliance on conventional synthetic pesticides towards approaches that reduce environmental loading, enhance target specificity, and improve residue monitoring and regulatory oversight. Several strategic directions have emerged as critical for achieving these objectives.

10.1 Expansion of Integrated Pest Management (IPM)

Integrated Pest Management (IPM) offers a scientifically robust framework for reducing dependence on synthetic pesticides through the combined use of biological control agents, crop rotation, resistant crop varieties, habitat manipulation, and targeted chemical interventions (Pretty & Bharucha, 2015).

From a chemistry standpoint, IPM decreases the total quantity of xenobiotic compounds introduced into agricultural ecosystems, thereby reducing residue accumulation, environmental persistence, and non-target toxicity. Lower pesticide inputs also decrease the selective pressure that drives the evolution of pesticide-resistant pest populations. This reduces the need for increasingly potent chemical formulations and prolongs the effectiveness of existing active ingredients.

Furthermore, reduced pesticide application frequencies allow natural degradation processes, including hydrolysis, photolysis, oxidation, and microbial metabolism, to proceed more effectively, promoting environmental recovery and lowering residue concentrations in crops and soils.

10.2 Development of Biopesticides from Plant and Microbial Sources

The development of biopesticides represents one of the most promising areas of modern agrochemical research. Biopesticides are derived from naturally occurring organisms or their metabolites and include botanical pesticides, microbial pesticides, and semiochemical-based products.

Chemically, many plant-derived biopesticides contain naturally occurring secondary metabolites such as alkaloids, terpenoids, flavonoids, limonoids, and phenolic compounds that possess insecticidal, fungicidal, or herbicidal activity (Isman, 2020). Examples include azadirachtin from *Azadirachta indica* (neem), pyrethrins from *Chrysanthemum cinerariifolium*, and essential oil constituents such as eugenol and thymol.

Microbial biopesticides utilise bioactive metabolites produced by bacteria, fungi, and viruses. For instance, *Bacillus thuringiensis* produces proteinaceous δ-endotoxins that selectively target insect larvae through receptor-mediated mechanisms. Compared with conventional synthetic pesticides, many biopesticides exhibit lower environmental persistence because their chemical structures are more readily degraded by biological and abiotic processes.

The expansion of biopesticide research in Nigeria could facilitate the development of locally sourced pest management solutions with reduced ecological footprints and improved environmental compatibility.

10.3 Precision Agriculture and Controlled Dosing Technologies

Precision agriculture employs advanced technologies to optimise agrochemical application based on spatial and temporal variability within agricultural fields. These technologies include geographic information systems (GIS), remote sensing, drone-based application systems, variable-rate technology, and automated spraying equipment.

From a chemical engineering perspective, precision application improves pesticide use efficiency by delivering active ingredients only where and when they are required. This minimises excess application, reduces environmental losses through drift and runoff, and decreases the accumulation of residues in soil and water systems (Gebbers & Adamchuk, 2010).

Controlled dosing technologies also improve the accuracy of formulation delivery, reducing concentration fluctuations that may affect efficacy and toxicity. By optimising dose-response relationships, precision agriculture can significantly reduce the overall chemical burden associated with crop protection practices.

10.4 Strengthening National Pesticide Regulatory Frameworks

Effective agrochemical management requires a robust regulatory framework capable of evaluating pesticide efficacy, toxicity, environmental fate, and residue behaviour before product registration and commercial

use.

From a regulatory chemistry perspective, strengthened pesticide legislation should incorporate comprehensive risk assessment procedures based on physicochemical properties, degradation kinetics, toxicological profiles, environmental persistence, and bioaccumulation potential (FAO & WHO, 2014). Enhanced post-registration surveillance is equally important for monitoring emerging contamination issues and ensuring continued compliance with safety standards.
Improved regulatory systems would help reduce the circulation of counterfeit products, prevent the use of highly hazardous pesticides, and promote the adoption of safer and more environmentally compatible alternatives.

10.5 Investment in Analytical Chemistry Infrastructure
The establishment and expansion of analytical chemistry facilities across Nigerian universities, research institutions, and regulatory laboratories are essential for strengthening pesticide management and food safety systems.

Modern residue analysis relies on sophisticated instrumentation, including gas chromatography–mass spectrometry (GC–MS), liquid chromatography–tandem mass spectrometry (LC–MS/MS), inductively coupled plasma mass spectrometry (ICP–MS), and high-resolution mass spectrometry (HRMS). These technologies enable the identification and quantification of pesticide residues, transformation products, and environmental contaminants at trace concentrations (Alder et al., 2006).

Investment in analytical infrastructure would improve national capacity for residue surveillance, environmental monitoring, toxicological investigations, and regulatory enforcement. It would also facilitate research into pesticide degradation pathways, metabolite formation, and exposure assessment within Nigerian agroecosystems.

10.6 Public Health Education and Chemical Safety Awareness
Public health education remains a critical component of sustainable agrochemical management. Many pesticide-related health risks arise not solely from the intrinsic toxicity of agrochemicals but from inappropriate handling, storage, mixing, and application practices.

From a chemical safety perspective, educational programmes should focus on the physicochemical hazards of pesticides, safe handling procedures, proper dilution techniques, personal protective equipment usage, residue minimisation strategies, and disposal methods. Increased awareness of concepts such as toxicity, exposure pathways, persistence, and bioaccumulation can improve decision-making among farmers and reduce occupational and environmental exposure.

Targeted educational campaigns in rural farming communities would be particularly beneficial, given the higher exposure risks often associated with limited access to technical information and healthcare services.

10.7 Emerging Opportunities in Green Agrochemical Chemistry
An additional future direction involves the application of green chemistry principles to pesticide design and formulation. Green agrochemical chemistry seeks to develop compounds that maintain efficacy while exhibiting lower toxicity, reduced persistence, enhanced biodegradability, and minimal non-target effects (Anastas & Warner, 1998).

Advances in molecular modelling, computational toxicology, nanotechnology, and controlled-release formulations are facilitating the development of next-generation agrochemicals with improved environmental profiles. Such innovations may enable Nigeria to adopt more sustainable crop protection strategies while maintaining agricultural productivity.

11. Conclusion
The application of pesticides and herbicides has become an integral component of commercial agriculture in Nigeria, playing a crucial role in enhancing crop productivity, reducing post-harvest losses, and supporting national food security. From a chemistry perspective, the effectiveness of these agrochemicals is governed by their molecular structures, physicochemical properties, mechanisms of action, and environmental behaviour. The diverse classes of pesticides and herbicides used in Nigerian agriculture, including organophosphates, carbamates, pyrethroids, organochlorines, neonicotinoids, glyphosate, atrazine, and 2,4-dichlorophenoxyacetic acid (2,4-D), exert their biological effects through highly specific interactions with enzymes, receptors, ion channels, and metabolic pathways. These interactions underscore the importance of chemical structure–activity relationships in determining both efficacy and toxicity.

This review demonstrates that the environmental fate of agrochemicals in Nigeria is strongly influenced by the country's tropical climatic conditions, soil characteristics, and agricultural practices. Processes such as hydrolysis, photolysis, oxidation–reduction reactions, sorption, volatilisation, leaching, and runoff govern the persistence, mobility, and transformation of pesticide residues within agricultural ecosystems. Consequently, pesticide and herbicide applications may result in the accumulation of residues in soils, surface waters, groundwater systems, crops, and other environmental compartments, particularly under conditions of intensive and repeated use.

The review further highlights the critical role of analytical chemistry in residue detection,

environmental monitoring, and food safety assessment. Advanced analytical techniques, including gas chromatography–mass spectrometry (GC–MS), liquid chromatography–tandem mass spectrometry (LC–MS/MS), and QuEChERS-based multi-residue methods, have significantly improved the capacity to identify and quantify agrochemical residues at trace concentrations. Nevertheless, limitations in analytical infrastructure, laboratory capacity, and residue surveillance programmes continue to constrain comprehensive monitoring efforts in Nigeria.

From a toxicological chemistry standpoint, pesticide and herbicide exposure remains an important public health concern. Occupational exposure through dermal absorption and inhalation, together with dietary exposure through contaminated food and water, has been associated with a range of adverse health outcomes, including acute poisoning, oxidative stress, cholinesterase inhibition, endocrine disruption, neurological impairment, and developmental toxicity. These risks are particularly pronounced among rural farming communities where awareness of chemical hazards, access to personal protective equipment, and healthcare resources may be limited.

Despite the existence of regulatory mechanisms, several challenges continue to undermine effective agrochemical management in Nigeria. Weak regulatory enforcement, the circulation of counterfeit and substandard pesticide products, inadequate farmer training, poor storage and handling practices, limited adoption of Integrated Pest Management (IPM), and insufficient residue monitoring systems collectively contribute to increased human exposure and environmental contamination. Addressing these challenges requires coordinated efforts involving government agencies, research institutions, regulatory bodies, agricultural extension services, and farming communities.

Looking forward, the adoption of sustainable and science-based approaches will be essential for improving agrochemical management in Nigeria. Increased implementation of IPM strategies, development of biopesticides derived from plant and microbial sources, application of precision agriculture technologies, strengthening of regulatory frameworks, expansion of analytical chemistry infrastructure, and enhancement of public health education programmes offer promising pathways towards reducing chemical risks while maintaining agricultural productivity.

In conclusion, the chemistry of pesticides and herbicides provides critical insights into their effectiveness, environmental behaviour, residue dynamics, and toxicological impacts. A comprehensive understanding of these chemical processes is fundamental for developing sustainable agricultural practices that balance crop protection needs with environmental stewardship and public health protection. Strengthening research, monitoring, regulation, and education will be pivotal in ensuring that agrochemical use in Nigeria contributes to long-term agricultural sustainability, food security, and ecological resilience.

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