

CLIMATE SMART AGRICULTURE, FOOD SECURITY AND SUSTAINABLE DEVELOPMENT

GLOBAL ISSUES & LOCAL PERSPECTIVES volume One

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CLIMATE SMART AGRICULTURE, FOOD SECURITY AND SUSTAINABLE DEVELOPMENT

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Preface

This book adopts an exegetical approach as well as a pedagogic model, making it attractive agriculture and environmental economics teachers, professional practitioners and scholars. It eschews pedantry and lays bare the issues in such clarity that conduces to learning. The book elaborates on contemporaneous **Climate Smart Agriculture, Food Security and Sustainable Development** issues of global significance and at the same time, is mindful of local or national perspectives making it appealing both to international and national interests. The book explores the ways in which climate smart agriculture (CSA) food security, Sustainable Development issues are and should be presented to increase the public's stock of knowledge, increase awareness about burning issues and empower the scholars and public to engage in the participatory dialogue climate smart agriculture, food security, and sustainable development necessary in policy making process that will stimulate increase in food production and environmental sustainability.

Climate Smart Agriculture, Food Security and Sustainable Development: Global Issues & Local Perspectives is organized in three parts. Part One deals with The Concept of **Climate Smart Agriculture**, Part Two is concerned with The Concept of **Food Security And** and Part Three deals with the Concept of **Sustainable Development**

Eteyen Nyong; October 2025

Chapter Seven

Climate-Smart Agriculture and Aquatic Toxicology: Balancing Food Security and Ecosystem Health

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1.0 Introduction

As global climate variability intensifies, agriculture is increasingly vulnerable to a range of environmental stressors, including uneven rainfall outlines, lengthened famines, intensified flooding, soil degradation, and heightened pest and disease pressures (Lombe, Carvalho & Rosa-Santos, 2024). These encounters not only compromise crop productivity and food security but also expose the limitations of conventional agricultural practices in adapting to and mitigating climate-induced disruptions (Aryal, Sapkota, Rahut, Krupnik, Shahrin, Jat & Stirling, 2020; FAO, 2021a; Malhi, Kaur & Kaushik, 2021). In response, Climate-Smart Agriculture (CSA) has gained momentum as an integrated approach to sustainably transform agri-food systems (Khumalo, Sibanda & Mdoda, 2024). Its core objectives are to enhance agricultural productivity, strengthen the resilience of farming communities, and reduce or remove greenhouse gas (GHG) emissions where possible (World Bank, 2022).

CSA integrates routines such as precision agriculture, conservation tillage, drought-resistant crop arrays, effective irrigation procedures and the judicious use of agrochemicals (Balasundram, Shamshiri, Sridhara & Rizan, 2023). When put into practice effectively, these approaches offer substantial benefits in acclimatizing to climate change while maintaining food production and ecosystem services. However, as CSA practices become more technologically intensive, apprehensions have surfaced around their broader environmental implications, particularly on aquatic ecosystems that are often the downstream recipients of agricultural inputs (Vasilachi, Asiminicesei, Fertu & Gavrilescu, 2021; Grigorieva, Livenets & Stelmakh 2023). Aquatic systems such as rivers, lakes, wetlands, and coastal zones are inherently sensitive to pollution due to their role in accumulating runoff and effluents from agricultural lands (Hussain, Ahmed, Muhammad, Awais, Zhang, Zhang, Raghavan, Zang, Zhao & Hu, (2025). Climate-smart interventions, especially those involving increased reliance on fertilizers, herbicides, pesticides, and newer inputs like nano-formulations or genetically modified organisms, may inadvertently introduce toxic substances into aquatic environments (Benbrook, Kegley & Baker, 2021). These

contaminants can disrupt aquatic food webs, alter physicochemical properties of water bodies, and pose chronic risks to biodiversity and human health through bioaccumulation and trophic transfer (Akinsemolu, 2023; Zhu, Li, & Song 2025).

Aquatic toxicology, the scientific study of how pollutants affect aquatic organisms, is therefore a crucial discipline for assessing the ecotoxicological risks of CSA (Kataoka & Kashiwada, 2021). It offers tools to examine both acute and chronic toxicity, sub-lethal biological responses, and ecosystem-level effects, using a combination of field, laboratory, and molecular techniques (Calisi, 2023). Understanding the ecological trade-offs of CSA practices through the lens of aquatic toxicology concedes for a more objective implementation ensuring that strategies designed to combat climate change do not inadvertently compromise water quality and aquatic health (Ojha, Behuria & Singh, 2025).

Moreover, climate change may intensify the toxic effects of agricultural pollutants through mechanisms such as increased water temperatures, altered precipitation patterns, and reduced dilution capacity of water bodies (Rajbanshi, Das & Paul, 2023). These climate-induced changes can enhance the solubility, bioavailability, and toxicity of contaminants, making their effects on aquatic life more severe and less predictable (Gomes, 2024)

Given these complexities, there is a pressing necessity to reassess CSA interventions within a multidisciplinary and ecotoxicologically informed framework. While CSA has proven potential in strengthening resilience and ensuring food security, its sustainability depends on addressing ecological trade-offs and unintended consequences (Khumalo *et al.*, 2024). Conventional approaches often overlook the downstream impacts of agricultural intensification on aquatic ecosystems, which function as vital reservoirs of biodiversity, water supply, and community livelihoods (Albou, Abdellaoui, Abdaoui & Ait, 2024). Without integrating aquatic perspectives, CSA risks perpetuating water pollution, wetland degradation, and the collapse of fragile aquatic food webs.

A truly sustainable CSA requires the integration of multiple domains of knowledge. Insights from climate science are critical for predicting hydrological shifts, extreme weather events, and long-term variability that influence pollutant dynamics in water bodies (Bărbulescu, Costache & Dumitriu, 2025). Toxicology and aquatic ecotoxicology provide the tools to evaluate the bioavailability, persistence, and organismal impacts of agrochemicals and emerging contaminants such as nanomaterials or pesticide mixtures (Albert & Bloem, 2023). Environmental policy and governance frameworks can ensure that regulatory safeguards, pollution thresholds, and monitoring protocols are aligned with international commitments like the Sustainable Development Goals (SDGs 2, 6, 13, and 14). Meanwhile, local and indigenous knowledge systems offer practical, context-specific strategies for water management and biodiversity conservation, often rooted in centuries of adaptive farming practices (Ijatuyi, Lamm, Yessoufou, Suinyuy & Patrick, 2025).

By weaving together these diverse perspectives, CSA can transition from a narrowly climate-focused agenda to one that is ecosystem-smart and aquatically sustainable. Such integration would support the design of nature-based solutions (e.g., constructed wetlands, buffer strips, integrated rice – aquaculture systems), participatory monitoring agenda that permits provincial villages to track water quality and policy innovations that harmonize agricultural intensification with aquatic ecosystem protection. Ultimately, an ecotoxicologically grounded CSA framework would safeguard food security and also the long-term resilience of freshwater and coastal ecosystems that heaps of people depend on for nutrition, livelihoods, and cultural identity.

2.0 Principles and Pillars of Climate-Smart Agriculture and Their Link to Aquatic Environments

Climate-Smart Agriculture (CSA) is built on three foundational pillars: productivity, resilience, and mitigation. While these goals aim to ensure food security and environmental sustainability while challenging climate change, they are intrinsically linked to the health of adjacent aquatic ecosystems both freshwater and marine (Figure 1). The pathways through which CSA practices interact with water bodies are complex and require critical evaluation to avoid trade-offs between terrestrial agricultural benefits and aquatic ecosystem integrity.

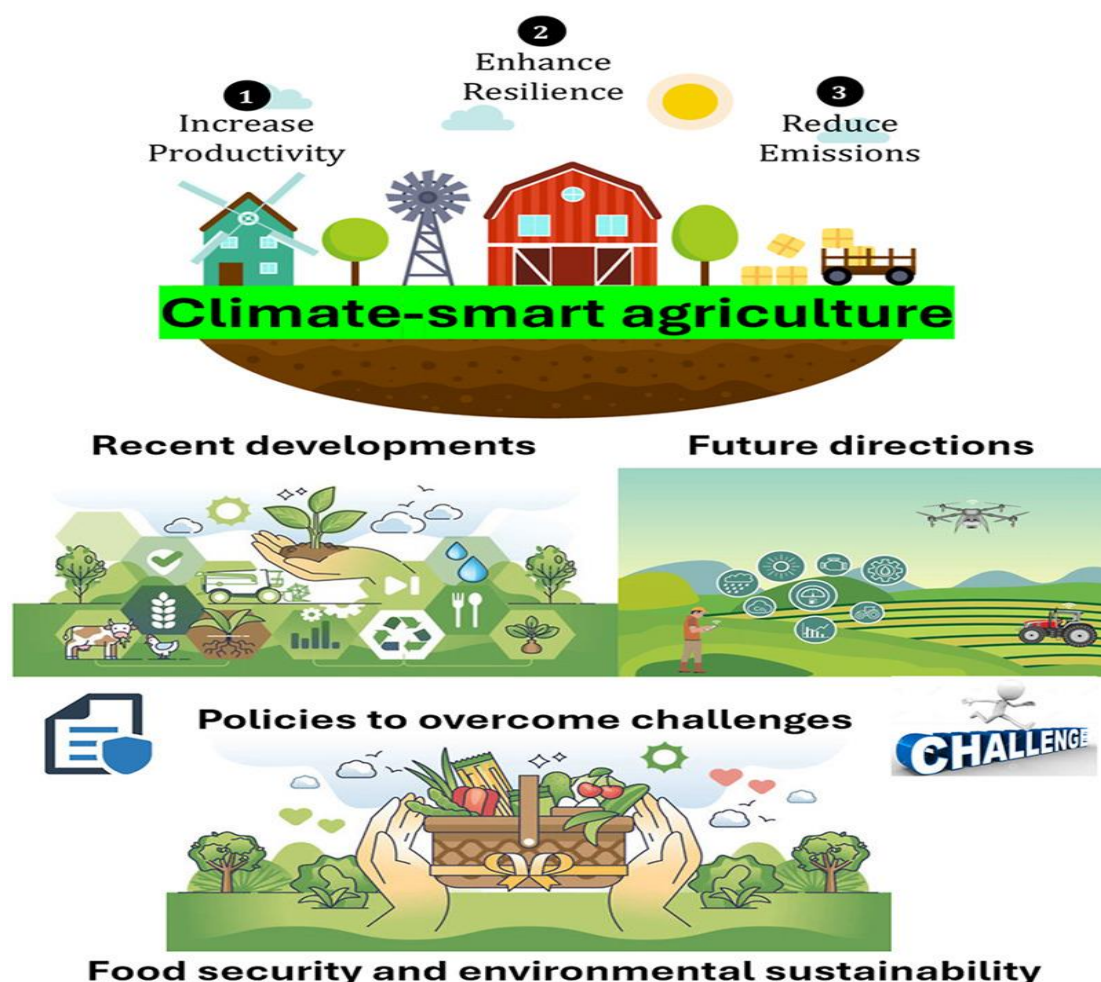


Figure 1: Multiple pathways to Climate Smart Agriculture

Source: Raihan, Ridwan & Rahman, (2024)

2.1 Productivity: Sustainable Yield Enhancement and Nutrient Runoff Risks

CSA promotes increased productivity through intensified farming practices such as precision agriculture, fertilizer optimization, and high-yield crop varieties. While these approaches reduce inefficiencies, they may inadvertently contribute to nutrient loading in nearby rivers, lakes, and coastal zones through agricultural runoff.

- a) **Link to Aquatic Systems:** Excess nitrogen and phosphorus from fertilizers even when applied with precision can leach into waterways, stimulating algal blooms, hypoxia, and eutrophication (Zhu *et al.*, 2025). These impacts threaten aquatic biodiversity and drinking water quality.

- b) CSA Mitigation Potential: Controlled-release fertilizers, buffer zones, and cover cropping can minimize nutrient leakage and protect aquatic habitats (Ali, Ahmad, Dar, Manan, Rani, Alghanem, Khan, Sethupathy, Elboughdiri, Mostafa, Alamri, Hashem, Shahid & Zhu, 2024).

2.2 Resilience: Adaptive Capacity and Agrochemical Contamination

CSA aims to build resilience against climate extremes by employing climate-resilient crop varieties, agroforestry, and conservation tillage. These strategies enhance soil structure, reduce erosion, and improve water retention. However, many resilience-enhancing interventions rely on chemical inputs like herbicides and biopesticides to maintain crop health under stress.

- a) Link to Aquatic Systems: These chemical agents can be mobilized by stormwater or irrigation return flows, entering aquatic systems and exerting toxicological effects on non-target organisms, such as amphibians, plankton, and fish (Calisi, 2023).
- b) CSA Mitigation Potential: Integrating biological pest control and adopting integrated pest management (IPM) can reduce reliance on harmful synthetic chemicals, lowering ecotoxicological risks to aquatic life.

2.3 Mitigation: Emissions Reduction and Aquatic Carbon Cycling

CSA contributes to climate mitigation by slashing the greenhouse gas emissions and enhancing carbon sequestration through practices such as agroforestry, manure management, and conservation agriculture.

- a) Link to Aquatic Systems: While these strategies help mitigate atmospheric CO₂ and CH₄, some can influence aquatic carbon dynamics. For example, poorly managed manure storage and biogas digesters may leak nutrients and pathogens into water bodies, degrading water quality and disrupting aquatic microbial processes (Rajbanshi *et al.*, 2023).
- b) CSA Mitigation Potential: Improved nutrient recycling, constructed wetlands, and anaerobic digesters with proper containment can transform agricultural waste into clean energy while protecting aquatic ecosystems.

2.4. Synthesis: The Need for Integrated Assessment

The environmental outcomes of CSA are not isolated to terrestrial systems. Each pillar, while crucial to climate adaptation and food security, involves management practices with direct and indirect consequences for aquatic health (Malhi *et al.*, 2021). Therefore, it is essential that CSA implementation is accompanied by:

- a) Ecotoxicological monitoring of runoff, sediments, and aquatic organisms;
- b) Landscape-scale planning to prevent habitat fragmentation and waterway contamination;
- c) Environmental Impact Assessments (EIAs) that include aquatic parameters;
- d) Water-smart farming that balances agricultural needs with aquatic ecosystem protection.

By embedding aquatic toxicology and water stewardship into CSA frameworks, the global agricultural transformation can proceed without undermining freshwater and marine biome services that are equally critical for planetary health.

3.0 Pathways of Agricultural Contaminants into Aquatic Systems

While Climate-Smart Agriculture (CSA) emphasizes sustainable productivity, resilience, and greenhouse gas mitigation, certain practices especially those involving agrochemicals or integrated systems can unintentionally introduce contaminants into aquatic environments (Raihan *et al.*, 2024). These pollutants threaten aquatic biodiversity, degrade water quality, and compromise human and animal health (Figure 2).

The primary pathways through which agricultural contaminants reach water bodies include:

3.1 Surface Runoff

Surface runoff is one of the direct and visible pathways for agricultural pollutants to enter aquatic systems. During rainfall or irrigation events, excess fertilizers (rich in nitrogen and phosphorus), pesticides, and herbicides applied to agricultural fields can be washed away into nearby rivers, lakes, and streams. This runoff is often accelerated on sloped terrains or poorly vegetated topsoil with low water permeation capacity. The nutrient-rich runoff fosters eutrophication in water bodies, leading to algal blooms, hypoxia, and fish kills (Lan, Liu, Hu & Zhu, 2024).

3.2 Leaching

Leaching refers to the downward movement of soluble contaminants, particularly nitrates and phosphates, through the soil into the groundwater (Shukla & Saxena, 2020). This pathway is prominent in areas with sandy or well-drained soils and high rainfall or irrigation rates.

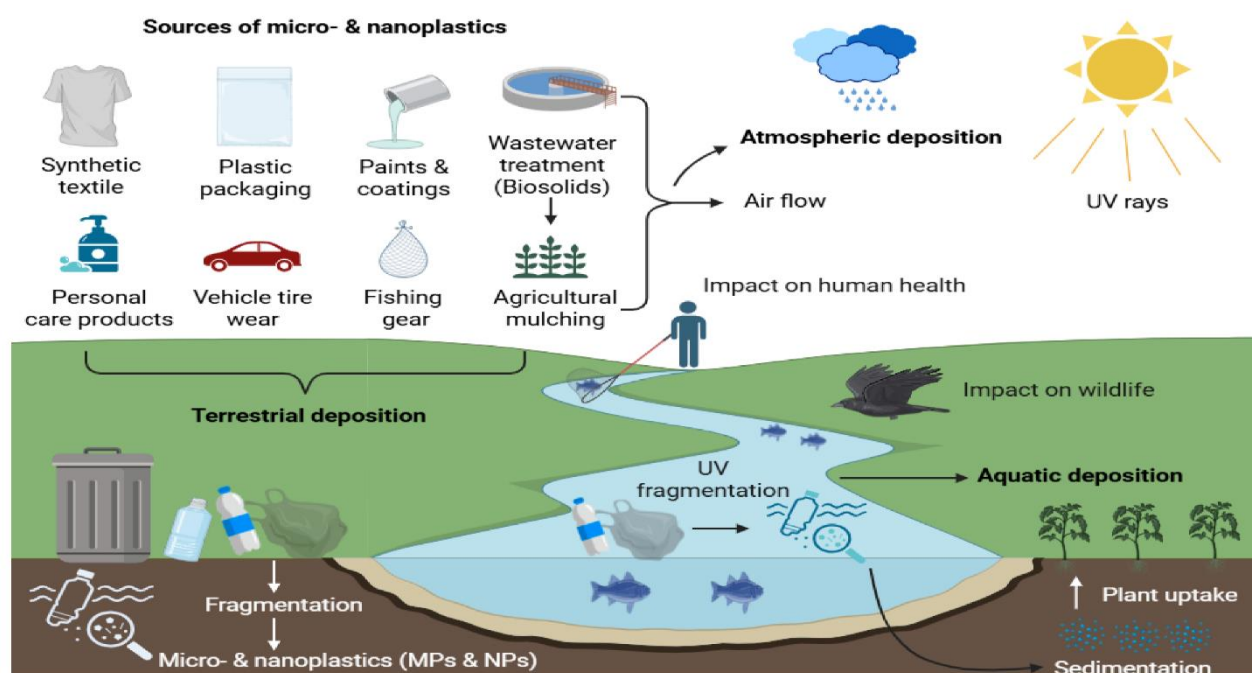


Fig 2: Exposure pathways of Anthropogenic Trace Compounds (ATCs) into the aquatic environment

Source: Bhardwaj, Abdulkadhim, Joshi, Wankhede, Das & Brar, (2025)

Once in the groundwater, these nutrients may stick around for a long time and eventually discharge into surface waters through springs or seepage zones (Akhtar, Syakir Ishak, Bhawani & Umar 2021). According to Chaudhary, Chauhan, Kale, Gosavi, Rathore, Dwivedi, Singh & Yadav, (2025), leaching poses significant risks to drinking water sources, contributing to nitrate contamination and related community health worries such as methemoglobinemia ("blue baby syndrome").

3.3 Spray Drift

Spray drift occurs when pesticides and herbicides applied via aerial spraying, boom sprayers, or mist blowers are carried by wind or air currents beyond the target area (Hong, Park, Jeong, H, Lee, Choi, Zhao, & Zhu, 2021). This unintentional drift can result in the deposition of toxic chemicals into nearby wetlands, streams, and reservoirs. Sensitive aquatic organisms, such as amphibians and invertebrates, are particularly vulnerable to low-dose chronic exposures from spray drift. Additionally, non-target vegetation near water bodies may be adversely affected, disrupting riparian ecosystems.

3.4 Aquaculture Waste

Integrated aquaculture-agriculture (IAA) systems, though resource-efficient, can contribute to aquatic pollution if not properly managed. Waste products from fish farming such as uneaten

feed, feces, and residues of antibiotics or chemotherapeutants can accumulate in surrounding waters. These inputs increase organic loads, elevate ammonia and nitrite concentrations, and contribute to microbial resistance. In open or semi-open systems, such wastes may gush into natural water forms, further compounding nutrient pollution and harming native aquatic fauna (Madjar, Vasile Scăețeanu, & Sandu, 2024).

4.0 Emerging Contaminants in Climate-Smart Agriculture

Climate-Smart Agriculture (CSA) aims to enhance sustainability and resilience, yet its adoption has brought forth novel inputs and technologies whose ecological risks especially in aquatic environments are still being fully understood. These emerging contaminants, though favorable for upgrading crop functioning and climate adaptability, may introduce new toxicological challenges for freshwater and marine ecosystems. Examples include:

a) Nano-fertilizers and Nano-pesticides

Engineered at the nanoscale, these materials promise enhanced nutrient use efficiency and targeted pest control (Zaman, Ayaz, & Park, 2025). However, due to their small size and high reactivity, nano-fertilizers and nano-pesticides can readily leach or wash into aquatic systems. Once in water, they may interact with aquatic organisms at the cellular or molecular level, causing oxidative stress, cytotoxicity, or disruption of metabolic functions. The long-term environmental persistence and bioavailability of nanomaterials remain a major concern (Kristanti, Hadibarata, Niculescu, Mihaiescu & Grumezescu, 2025).

b) Biologicals (e.g., Bioinoculants, Microbial Agents)

CSA often promotes biologicals as alternatives to synthetic agrochemicals. These include nitrogen-fixing bacteria, mycorrhizal fungi, and biocontrol microbes. While generally seen as eco-friendly, the large-scale application of living microbial agents raises questions about their survival, horizontal gene transfer, and potential ecological imbalances when they enter aquatic systems (Lajqi Berisha, Poceva Panovska, & Hajrulai-Musliu, 2024). Some strains may outcompete native microbial communities, altering nutrient cycling and aquatic food web dynamics.

c) Genetically Engineered Organisms (GEOs)

Genetically modified crops and microbes developed for climate resilience (e.g., drought tolerance, pest resistance) can release novel proteins, enzymes, or metabolites into the environment. Runoff from fields cultivating GEOs may carry DNA fragments or transgene products into water bodies, potentially affecting aquatic microbiota and invertebrates. The ecological effects of such exposure, particularly under changing climate conditions, are still under active investigation (Thammatorn & Palić, 2022).

d) Climate-Resilient Agrochemicals

New-generation agrochemicals designed to remain effective under extreme weather conditions (e.g., higher temperatures, altered rainfall patterns) may also exhibit increased persistence or reactivity in the environment. Their physicochemical properties may enhance solubility or resistance to degradation, increasing their likelihood of entering and persisting in aquatic systems.

4.1 Toxicological Concerns in Aquatic Environments

The presence of these emerging contaminants in aquatic systems raises multiple toxicological issues:

- a) Sub-lethal effects on fish: Many emerging contaminants do not cause immediate mortality but may lead to long-term physiological disruptions such as endocrine imbalance, immunosuppression, and oxidative stress, reducing fitness and reproductive success in fish populations (Peskova & Blahova, 2025).
- b) Bioaccumulation: Nanoparticles, synthetic organics, and even microbial metabolites can accumulate in the tissues of aquatic organisms, magnifying through the food web and affecting top predators, including humans (Kristanti *et al.*, 2025).
- c) Synergistic effects with climate change: Rising water temperatures and pH fluctuations can exacerbate contaminant toxicity. Warmer temperatures may increase chemical solubility, uptake rates, and metabolic stress in aquatic species, compounding the impact of low-level exposures (Matthee, Brown, Lange & Tyler, 2023).

Table 1: Emerging Contaminants in Climate-Smart Agriculture and Their Aquatic Impacts

S/N	Contaminant Type	Examples	Pathways to Aquatic Systems	Potential Impacts on Aquatic Environments
1	Nano-fertilizers & Nano-pesticides	Nano-urea, nano-silver, nano-copper	Surface runoff, leaching, spray drift	- Oxidative stress and cytotoxicity in fish and plankton - Disruption of microbial balance - Bioaccumulation
2	Biologicals (Bioinoculants)	Rhizobia, Trichoderma spp., mycorrhizae	Leaching, runoff, direct introduction, IAA	- Alteration of native microbial communities - Changes in nutrient cycling - Potential gene transfer risks
3	Genetically Engineered Organisms	Crops, drought-tolerant GMOs, GE microbes	Surface runoff, erosion, decaying biomass	- Release of transgene products into water - Effects on non-target aquatic organisms - Unknown long-term risks
4	Climate-resilient Agrochemicals	Heat-stable pesticides, slow-release herbicides	Runoff, leaching, spray drift	- Increased persistence and mobility in water - Toxicity under high temperature/pH - Synergistic climate effects

5	Aquaculture Products	Waste	Antibiotic residues, excess feed, hormones	Effluent from integrated systems	discharge - integrated	- Eutrophication - antimicrobial resistance	- Spread of
						- Toxic effects on benthic organisms and fish	

*** IAA – Integrated Aquaculture – Agriculture; GMOs – Genetically Modified Organisms; GE – Genetically Engineered

5.0 Aquatic Toxicology: Mechanisms and Impacts

Aquatic toxicology examines the interactions between chemical pollutants and aquatic organisms, elucidating the pathways, mechanisms, and consequences of toxic exposure (Pal Prabhakar, Barua, Zekker, Burlakovs, Krauklis, Hogland & Vincevica-Galle, 2025). With the proliferation of climate-smart agricultural inputs ranging from nano-agrochemicals to biological agents, the need to understand their ecological and toxicological implications in freshwater and marine systems has intensified. This section explores the principal toxicological mechanisms and their cascading impacts on aquatic ecosystems.

5.1 Acute and Chronic Toxicity

Toxicity assessments form the foundation of aquatic toxicology, distinguishing between acute toxicity immediate, short-term harmful effects and prolonged noxiousness, which emanant from long-term, low-level exposure (Stubblefield, Barron, Bragin, DeLorenzo, de Jourdan, Echols, French-McCay, Jackman, Loughery, Parkerto, Renegar & Rodriguez-Gil, 2023). Standard toxicological endpoints include:

- LC₅₀ (Lethal Concentration 50%): Concentration at which 50% of test organisms die within a specified period.
- EC₅₀ (Effective Concentration 50%): Concentration inducing a specific sub-lethal effect (e.g., immobility, abnormal behavior).
- NOEC (No Observed Effect Concentration): Highest concentration at which no statistically significant effects are detected.

These metrics are habitually derived from standardized bioassays using model organisms such as *Danio rerio* (zebrafish), *Daphnia magna*, and *Xenopus laevis* (Sá, Michelin, Tavares & Silva, 2022; Kristanti *et al.*, 2025).

Latest documentations have indicated that emerging contaminants such as nano-pesticides and bio-stimulants can exhibit unexpectedly high chronic toxicity even at concentrations below traditional acute thresholds (Kristanti *et al.*, 2025). Additionally, climate-induced stressors such as warming or acidification can exacerbate toxic effects, leading to synergistic interactions not accounted for in conventional risk models (Pikula, Johari, Santos-Oliveira & Golokhvast, 2024).

5.2 Biomarkers

Biomarkers are molecular, biochemical, or physiological indicators that signal early exposure or effects of toxicants before population-level consequences emerge. They provide a sensitive and diagnostic means to assess contaminant impact.

- a) **Enzymatic Biomarkers:** Inhibition of acetylcholinesterase (AChE) is a well-documented marker for exposure to organophosphate and carbamate pesticides. AChE inhibition has been linked to neuromuscular dysfunction in fish and invertebrates (Formicki, Goc, Bojarski, & Witeska, 2025).
- b) **Oxidative Stress Biomarkers:** Elevated degrees of reactive oxygen species (ROS) and shifts in antioxidant enzyme activity (e.g., catalase, glutathione peroxidase, superoxide dismutase) are common responses to exposure to nanomaterials and pesticides (Bonzini, Leso & Iavicoli, 2022).
- c) **Genotoxicity:** DNA damage, micronuclei formation, and chromosomal aberrations are indicative of long-term mutagenic effects. These biomarkers have been re-counted in fish and mollusks (Ayoola, Ejikeme & Akinjogunla, 2024).

Collectively, biomarkers enable early detection of ecological risk, facilitating regulatory responses and environmental monitoring frameworks.

5.3 Trophic Transfer

Trophic transfer refers to the bioaccumulation (build-up of contaminants in an organism) and biomagnification (increase in contaminant concentration along the food web). Contaminants such as heavy metals, persistent organic pollutants (POPs), and engineered nanomaterials readily move from primary producers and consumers (e.g., phytoplankton, zooplankton) to higher trophic levels (e.g., fish, birds, humans).

Recent studies have documented the trophic transfer of plastic-associated pollutants and nanoplastics in freshwater and estuarine systems (Thammatorn & Palić, 2022; Amobonye, Bhagwat, Raveendran, Singh & Pillai, 2021). The complexity of contaminant mixtures (e.g., co-existence of metals, pesticides, and microplastics) enhances their mobility and toxicity, often resulting in immunosuppression, behavioral alteration, and reproductive failure in apex predators (Vasilachi *et al.*, 2021).

5.4 Ecological Effects

Beyond individual-level toxicity, contaminants impact ecological structure and function. Key effects include:

- a) **Eutrophication:** Excessive input of nitrogen and phosphorus from fertilizers triggers harmful algal blooms, leading to hypoxia, fish kills, and loss of aquatic flora. This is a growing concern in intensively farmed watersheds (UNEP, 2023).
- b) **Loss of Biodiversity:** Exposure to pesticides, pharmaceuticals, and nanoparticles reduces species richness and alters community composition in aquatic ecosystems (Albert & Bloem, 2023). Sensitive taxa such as amphibians and benthic macroinvertebrates are especially vulnerable.

- c) Disruption of Life Cycles: Endocrine-disrupting compounds (EDCs) interfere with hormone signaling in fish, affecting spawning, sex differentiation, and larval development (Gałązka & Jankiewicz, 2022). Seasonal migratory patterns and population recruitment are also disrupted by thermal and chemical stressors.

These ecological impacts undermine critical ecosystem services such as fisheries productivity, water purification, and climate regulation.

6.0 Climate Change, Climate-Smart Agriculture (CSA) and Toxicological Interactions

Climate change introduces complex pointers that intermingle with the toxicological profiles of agricultural pollutants. In aquatic systems, changing temperatures, precipitation patterns, and biogeochemical cycles significantly alter the fate, behavior, and impacts of agrochemicals. As such, climate change is often referred to as a "toxicant multiplier", a force that intensifies both the exposure and effects of contaminants introduced through Climate-Smart Agriculture (CSA) practices.

6.1 Increased Toxicity at Higher Water Temperatures

Rising global temperatures, particularly in tropical and subtropical regions, increase water temperatures in rivers, lakes, and irrigation canals. Higher temperatures enhance the metabolic rates of aquatic organisms, accelerating uptake and biotransformation of toxicants, which may lead to increased bioavailability and toxicity of contaminants even at lower concentrations (Bonacina, Fasano, Mezzanotte & Fornaroli, 2022).

For instance, raised temperatures have been revealed to enhance the toxicity of pesticides, such as glyphosate and atrazine, by reducing their degradation rates and increasing their reactivity with cellular components in fish and invertebrates (Lacy & Rahman, 2022). Warmer water also intensifies the toxicity of ammonia, commonly present in aquaculture and CSA runoff, especially in shallow, low-flow systems. At higher temperatures, the un-ionized form of ammonia (NH_3), which is far more toxic than its ionized counterpart (NH_4^+), becomes more prevalent and harmful to fish gills and nervous systems.

6.2 Altered Chemical Speciation and Solubility

Temperature, pH, and redox potential all influenced by climate change modify the speciation and solubility of contaminants, especially metals. For example:

- a) Cadmium and mercury become more soluble and bioavailable under acidic and hypoxic conditions, increasing their uptake by aquatic organisms (Zhao, Zhao, Cui, Zhang & Zhang, 2024).
- b) Nanomaterials such as zinc oxide or silver nanoparticles, used in CSA nano-fertilizers, exhibit increased dissolution at higher temperatures, leading to greater ion release and oxidative stress (Kristanti *et al.*, 2025).

These changes in chemical form significantly affect how pollutants interact with biological membranes, with potential consequences for genotoxicity, enzymatic inhibition, and endocrine disruption.

6.3 Decline in Dissolved Oxygen (DO)

Higher water temperatures and increased microbial activity (often stimulated by nutrient-rich runoff from CSA) reduce dissolved oxygen (DO) levels in aquatic environments. Hypoxia not only stresses aquatic organisms but also:

- Decreases their detoxification capacity by impairing hepatic metabolism.
- Enhances the toxicity of pollutants, particularly organophosphates and pharmaceuticals (Rico *et al.*, 2021).
- Promotes anaerobic conditions that transform nitrogenous compounds into more toxic forms such as nitrite (NO_2^-) and ammonia (NH_3) (Ali, Anushka & Mishra (2022).

Reduced DO also facilitates poisonous algal eutrophication, which could release additional toxins and compete with aquatic life for oxygen.

6.4 Disrupted Hydrological Cycles and Pollutant Mobilization

Climate-induced changes in rainfall patterns such as more intense storms and longer droughts impact hydrological connectivity and pollutant transport:

- Heavy rainfall and flooding increase surface runoff, transporting agrochemicals, sediments, and pathogens into nearby water bodies (UNEP, 2023a).
- Droughts and reduced river flow lead to pollutant concentration in stagnant waters, increasing exposure for aquatic life (Pikula *et al.*, 2024).
- Altered seasonal water levels can remobilize previously buried contaminants in sediments, such as phosphorus or legacy pesticides.

These changes affect not only pollutant concentrations but also their spatial and temporal dynamics, complicating environmental management and regulation.

Table 2: Climate Change as a Toxicant Multiplier in Aquatic Systems

S/N	Climate Factor	Change	Mechanism of Interaction	Resulting Impact on Contaminant Behavior and Toxicity
1	Elevated Temperature	Water	Increases metabolic rates of aquatic organisms and chemical reaction rates	- Enhances uptake and biotransformation of pollutants - Increases un-ionized ammonia (NH_3) toxicity
2	Altered Speciation	Chemical	Temperature, pH, and redox shifts change the form and solubility of metals and nanomaterials	- Greater solubility and bioavailability - Increased cellular toxicity
3	Reduced Dissolved Oxygen (DO)	Dissolved	Warmer water holds less oxygen; eutrophication and	- Impairs detoxification in fish - Increases sensitivity to pollutants under hypoxia

			microbial activity further deplete oxygen	
4	Extreme Events Flooding)	Weather (Rainfall,	Enhanced runoff and erosion increase chemical and pathogen entry into water bodies	- Increases pollutant loads and sediment - bound toxin mobilization
5	Drought and Flow Conditions	Low	Water stagnation and evaporation concentrate pollutants	- Higher contaminant concentrations and prolonged exposure for aquatic organisms
6	Hydrological Disruption		Changes in flow regimes remobilize legacy pollutants from sediments	- Re-exposure to old contaminants (e.g., phosphorus, pesticides) - Increases bioaccumulation risks

7.0 Risk Assessment and Monitoring Approaches

Effective protection and sustainable management of Nigeria's wetlands require robust tools for identifying, quantifying, and responding to ecological threats. As wetland ecosystems face increasing pressure from pollution, climate change, and anthropogenic activities, it is essential to deploy integrated risk assessment and environmental monitoring approaches that reflect both local ecological contexts and global environmental changes. Highlighted below are four key tools and methods:

7.1 Environmental Risk Assessment (ERA)

Environmental Risk Assessment is a systematic framework for evaluating the likelihood and severity of hostile ecological impacts stemming from contact to chemical, biological, or physical stressors. It includes four core components: hazard identification, exposure assessment, dose response assessment, and risk characterization (USEPA, 2021). In wetland environments, ERA is used to review the risks of agrochemicals, industrial effluents, and heavy metals to aquatic flora and fauna.

Recent advancements have led to the advancement of spatially explicit ERA models that incorporate hydrological connectivity, land use data, and climate variables to better understand pollutant dispersion and exposure pathways in wetland catchments (Zhao, Wu, Zhang, Yu, & Sun, 2025). For instance, probabilistic models and species sensitivity distributions (SSDs) are being applied to quantify the likelihood of ecosystem-level effects under multiple stressor scenarios, including pesticide runoff and nutrient loading.

7.2 Biomonitoring with Sentinel Species

Biomonitoring involves the utilization of living organisms sentinel species to appraise the cumulative impacts of environmental stressors on biological systems. Commonly used species in Nigerian wetland studies include:

- a) *Clarias gariepinus* (African catfish): Known for its resilience and wide distribution, this species is used to assess heavy metal and pesticide toxicity through bioaccumulation studies and histopathological analysis.
- b) *Daphnia magna*: A freshwater zooplankton sensitive to a widespread scope of pollutants, especially endocrine-disrupting chemicals.
- c) *Oreochromis niloticus* (Nile tilapia): Often used in chronic toxicity and biomarker studies related to oxidative stress, enzyme activity (e.g., acetylcholinesterase), and reproductive impairments.

These organisms provide early-warning indicators of ecological stress and help track sublethal and cumulative effects over time (Hazen, Savoca, Clark-Wolf, Czapanskiy, Rabinowitz & Abrahms, 2024). Integration of bioindicator data with GIS mapping enhances spatial monitoring and pollution source identification.

7.3 Ecotoxicogenomics

The emerging field of ecotoxicogenomics uses high-throughput molecular tools/ gears such as transcriptomics, proteomics, and metabolomics to detect changes in gene and protein expression in organisms exposed to environmental contaminants. These gears facilitate early exposure of cellular and molecular stress responses, often before physiological or behavioral symptoms manifest.

In Nigeria, recent studies have applied transcriptomic analyses in *Clarias gariepinus* and *Oreochromis niloticus* exposed to oil-derived polycyclic aromatic hydrocarbons (PAHs) and agricultural runoff, revealing altered expression of genes related to oxidative stress, immune function, and apoptosis (Iyora, Enagbonma, Abu & Biose, 2023). These biomarkers are imperative for mechanistic understanding of contaminant effects and for developing molecular endpoints for environmental monitoring.

7.4 Climate-Adjusted Toxicological Thresholds

Traditional environmental quality standards often do not consider the interactive effects of climate variables, such as increased water temperature, altered pH, or decreased dissolved oxygen, on contaminant toxicity. Contemporary research demonstrates that chemical toxicity can be amplified under climate change conditions, necessitating the revision of ecological thresholds (Boxall *et al.*, 2022).

For instance, rising temperatures have been disclosed to increase the metabolic rates and uptake of pesticides in aquatic organisms, thereby reducing the safety margins of current environmental limits. Climate-adjusted ERA models are being developed to incorporate climate projections and dynamic exposure scenarios, especially for tropical wetland ecosystems where climate stressors are already acute (Olunusi & Adeboye, 2025).

The integration of traditional and cutting-edge tools ranging from classical ERA and field biomonitoring to omics technologies and climate-responsive modeling provides a multidimensional approach to assessing ecological risks in Nigeria's wetlands. Developing

context-specific thresholds, enhancing institutional capacity, and promoting open-access environmental databases will be critical for adaptive and resilient wetland management.

8.0 Strategies for Mitigating Aquatic Risks in Climate-Smart Agriculture (CSA)

The integration of aquatic ecosystem protection into Climate-Smart Agriculture (CSA) frameworks is essential to ensuring that agricultural intensification and climate adaptation do not come at the cost of wetland degradation, water pollution, or biodiversity loss. This section outlines a multi-tiered approach to mitigating aquatic risks through strengthened policy and governance, adoption of best management practices (BMPs), and leveraging technology and innovation.

8.1 Policy and Governance

Governance frameworks enact a pivotal function in aligning CSA strategies with water quality and ecosystem health objectives. The following actions are recommended:

- a) **Enforce Buffer Zones Around Water Bodies:** Regulatory policies should mandate vegetative buffer zones of appropriate width (10–50 m, depending on slope and land use intensity) around rivers, lakes, and wetlands to trap sediments, nutrients, and agrochemicals before they reach aquatic systems (FAO, 2021b). These buffers also help preserve riparian biodiversity and moderate stream temperatures.
- b) **Develop Agrochemical Regulations Specific to CSA:** National pesticide and fertilizer policies should be revised to promote climate-smart inputs that reduce volatilization, runoff, and leaching. This includes encouraging slow-release fertilizers, biopesticides, and integrated pest management (IPM) compatible with CSA (Izuogu, Oparaojiaku, Olaolu, Iroegbu, Ifabiyi, Ayegboyin & Ominikar, 2025).
- c) **Include Aquatic Risk Screening in CSA Policy Frameworks:** Risk assessments for CSA programs should incorporate aquatic ecosystem impact indicators, particularly in wetland-rich agro-ecological zones. CSA subsidies and incentives can be tied to compliance with water protection standards.

8.2 Best Management Practices (BMPs)

CSA's ecological goals can be achieved on-farm through well-established and adaptive BMPs that reduce aquatic contamination:

- a) **Vegetative Strips and Buffer Crops:** Planting strips of perennial grasses or legumes along field margins reduces surface runoff, traps sediment-bound nutrients, and stabilizes soil (Diop, Chirinda, Beniaich, El Gharous & El Mejahed, 2022).
- b) **Controlled-Release Fertilizers and Nutrient Timing:** The use of encapsulated or coated fertilizers minimizes nutrient loss during rainfall events. Synchronizing fertilizer application with crop nutrient demand also lowers excess runoff.
- c) **Use of Biopesticides and Organic Soil Amendments:** Substituting synthetic pesticides with microbial or plant-based biopesticides reduces aquatic toxicity. Compost and biochar improve soil health and reduce nutrient leaching (Malinga & Laing, 2022).

- d) **Water Recycling and Closed-Loop Systems:** In aquaponics and integrated CSA systems, recycling water reduces nutrient loss to the environment and creates synergies between crop and fish production.

8.3 Technology and Innovation

Technological innovations provide powerful tools for detecting, predicting, and minimizing aquatic pollution in CSA landscapes:

- a) **Precision Irrigation and Fertigation:** Technologies such as drip irrigation, soil moisture sensors, and fertilizer injectors help deliver water and nutrients efficiently, reducing runoff and infiltration into aquatic ecosystems (Onyango, Nyaga, Wetterlind, Söderström & Piikki, 2021).
- b) **Remote Sensing and GIS for Pollution Monitoring:** Satellite and drone-based monitoring of land use change, vegetation health, and surface water quality enable rapid identification of pollution hotspots, enabling targeted interventions (Isukuru, Opha, Isaiah, Orovwighose, Emmanuel, 2024).
- c) **Wetlands Restoration and Constructed Wetlands:** Restoring degraded wetlands or constructing artificial wetlands near farms provides natural filtration of nutrients, pathogens, and pesticides. These techniques can also function as buffers against climate - driven floods (Hsu, Yan, Pan & Lee, 2021).

Mitigating aquatic risks in CSA requires an integrated strategy that combines science-based policy, adaptive farm-level practices, and data-driven innovations. As climate variability intensifies, ensuring the resilience of both agricultural and aquatic ecosystems will depend on cross-sector collaboration, inclusive governance, and the scaling-up of tested BMPs and green technologies.

9.0 Toward Integrated CSA – Aquatic Health Systems

The challenges of climate change, agricultural intensification, and aquatic ecosystem degradation necessitate a holistic, systems-based approach to Climate-Smart Agriculture (CSA). While CSA traditionally emphasizes productivity, adaptation, and mitigation, its long-term sustainability relies on the health of aquatic biotas, which are crucial for food security, biodiversity, water purification, and climate resilience. The major supports for fostering integrated CSA – Aquatic Health Systems, grounded in the One Health framework and supported by ecological stewardship and inclusive governance are:

9.1 Harmonizing Agricultural Productivity with Aquatic Ecosystem Protection

Integrated CSA – aquatic systems recognize that the drive for increased food production must not compromise wetland integrity, water quality, or aquatic biodiversity. This requires:

- a) **Land-use zoning** that distinguishes conservation, buffer, and production areas in agro-ecological landscapes.
- b) **Eco-efficiency targets** for farms, including reduced agrochemical runoff and water use per unit yield.

- c) Adoption of agroforestry, conservation tillage, and integrated nutrient management to reduce downstream impacts (Altieri & Nicholls, 2020).

By aligning agricultural practices with ecosystem protection goals, such systems ensure both food and water security.

9.2 Embracing One Health Principles

The One Health concept promotes the interconnectedness of human, animal, and environmental health. In the context of CSA and wetlands, this perspective emphasizes:

- a) Preventing zoonotic disease spillovers from stressed aquatic environments where poor water quality fosters pathogen transmission.
- b) Addressing antimicrobial resistance (AMR) linked to intensive aquaculture and runoff of veterinary drugs (Tao, Haihong, Xiaolin & Jiang, 2023).
- c) Ensuring that agricultural water management protects both ecosystem and public health, especially in rural communities relying on wetland resources.

Incorporating One Health into CSA reinforces the idea that healthy ecosystems underpin resilient food systems and human well-being.

9.3 Community Engagement and Transdisciplinary Collaboration

Sustainable integration requires active participation of local communities, traditional knowledge holders, scientists, policymakers, and farmers:

- a) Community-based monitoring programs enable early detection of ecological changes (e.g., fish kills, water turbidity, or invasive species).
- b) Indigenous ecological knowledge (IEK) helps tailor CSA practices to local wetland conditions, such as seasonal water dynamics and soil fertility.
- c) Transdisciplinary research platforms foster co-creation of knowledge, linking agronomists, hydrologists, ecologists, public health experts, and social scientists (Rangecroft, Rohse, Banks, Day, Di Baldassarre, Frommen, ... & Van Loon, 2020).

This inclusive approach ensures context-specific solutions and long-term ownership of interventions.

9.4 Supporting Nature-Based Solutions and Integrated Production Systems

Nature-based solutions (NbS) provide win-win strategies for climate adaptation, biodiversity conservation, and food production. Key examples include:

- a) Agroecology: Emphasizes biodiversity, soil health, and ecological resilience. Agroecological zones designed to include wetland protection can limit runoff and enhance aquatic habitat connectivity (FAO, 2021c).
- b) Aquaponics and Integrated Agriculture – Aquaculture (IAA): These closed-loop systems reduce nutrient loss to the environment, minimize water use, and enhance food diversity by combining plant and fish production (Ibrahim, Shaghaleh, El-Kassar, Abu-Hashim, Elsadek & Alhaj Hamoud, 2023).

- c) Constructed wetlands and riparian reforestation: These act as biofilters for agricultural runoff and restore hydrological functions critical for ecosystem services.

By embedding these innovations into CSA programs, practitioners can create regenerative agricultural landscapes that nurture both terrestrial and aquatic life.

10.0 Conclusion

Climate-Smart Agriculture (CSA) offers a pathway to resilient and sustainable food systems, but its long-term success depends on integrating aquatic health and ecosystem protection. Embedding aquatic toxicology into CSA helps assess and mitigate risks such as water pollution, wetland loss, and biodiversity decline.

To be truly resilient, CSA must evolve into an ecosystem-smart model that balances productivity with ecological integrity through safeguards, nature-based solutions, One Health principles, and community participation. For Nigeria and other nations, aligning agricultural growth with aquatic conservation is key to achieving food security without compromising environmental sustainability.

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