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Review

Effect of Pesticide and Nutrient Losses from Smallholder Farms on Surface Water Quality in Eastern Africa: A Systematic Review

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Abstract

Agricultural intensification in Eastern Africa has raised concerns about the transport of pesticides and nutrients from farmland into surface waters, posing risks to ecosystems and human health. This study systematically reviews the peer-reviewed literature published between 2010 and 2024 to assess the extent, patterns, and drivers of agrochemical contamination in rivers, lakes, and reservoirs across the region. Reported pesticide concentrations ranged from <0.01 to 0.55 μg L^{-1}, with several studies indicating exceedances of drinking-water or environmental guideline values, particularly for organophosphate and carbamate compounds. Nutrient enrichment was widespread, with nitrate concentrations of 0.99–5.6 mg L^{-1} and phosphate levels of 0.16–2.0 mg L^{-1}, frequently linked to eutrophication. Many studies showed strong seasonal variability, with higher concentrations during rainy periods due to increased runoff and erosion. Variability among findings reflected differences in land use, catchment characteristics, sampling design, and analytical approaches. Where evaluated, mitigation measures such as vegetated buffer strips, cover cropping, and improved nutrient management were associated with reductions in agrochemical runoff of approximately 50–80%. Overall, agrochemical contamination is widespread across Eastern African basins and influenced by agricultural practices and hydrological dynamics, highlighting the need for strengthened monitoring, improved stewardship, and broader adoption of mitigation strategies.

Keywords: agricultural intensification; Eastern Africa; eutrophication; nutrient losses; pesticide contamination; smallholder farms; surface water quality; sustainable land management

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Academic Editor: Annabel Fernandes

Received: 25 March 2026
Revised: 12 June 2026
Accepted: 16 June 2026
Published: 20 June 2026

1. Introduction

Surface water quality degradation is an escalating environmental and public health concern across Eastern Africa, driven by the intensification of agricultural production and associated non-point source pollution. Among the principal contaminants are pesticides and nutrients, which are increasingly detected in rivers, lakes, and reservoirs that sustain domestic water supply, fisheries, irrigation, and ecosystem services [1,2]. In regions where smallholder agriculture dominates food production systems, agrochemical inputs have become central to yield stabilization; however, their mismanagement can result in significant off-site transport through surface runoff and leaching, leading to contamination of adjacent surface waters [3,4].

Smallholder farming systems contribute substantially to food security, rural employment, and national economies across Eastern Africa [5,6]. Within these systems, farmers widely apply fertilizers and pesticides to improve crop yields and manage pests and diseases [7]. Yet limited access to extension services, inadequate training on recommended application rates, and inappropriate handling practices frequently result in over-application and unsafe use of agrochemicals, exacerbating environmental risks [8]. These practices increase the likelihood of agrochemical mobilization through surface runoff, leaching, and soil erosion, particularly during intense rainfall events. Such seasonal and episodic runoff events reflect natural hydrologic variability, whereas long-term climate change projections (e.g., IPCC) anticipate shifts in the frequency and intensity of extreme precipitation events, representing a distinct mechanism of risk [9,10].

Early regional syntheses identified agricultural non-point source pollution from smallholder systems as a dominant driver of eutrophication in sub-Saharan Africa, especially in catchments characterized by high population density and intensified smallholder cultivation, highlighting the vulnerability of water resource systems [11]. Nutrient enrichment from nitrogen and phosphorus inputs promotes harmful algal blooms (HABs), hypoxia, altered trophic dynamics, and biodiversity loss in freshwater ecosystems [12–14].

Concurrently, pesticide contamination, including widely used organophosphates, carbamates, pyrethroids, and persistent legacy compounds such as DDT, can remain in aquatic environments for extended periods, bioaccumulate in food webs, and disrupt aquatic biodiversity [15,16]. In some cases, the presence of DDT in aquatic environments reflects legacy residues from illegal indoor residual spraying for malaria control, rather than current smallholder agricultural inputs. These effects can alter ecosystem functioning such as food-web dynamics, invertebrate community structure, and reduce ecosystem services. Consequently, water quality may deteriorate, affecting domestic supply, irrigation, and fisheries, and may increase risks of human exposure through contaminated fish and drinking water sources [17,18].

Beyond individual compounds, aquatic environments frequently receive complex mixtures of pesticides and nutrients. Experimental evidence shows that environmentally realistic pesticide mixtures can interact to affect primary consumers and community structure in agricultural streams [19]. Moreover, combined exposure to nutrients and pesticides has been shown to significantly alter algal biomass and zooplankton abundance, suggesting interactive effects that differ from single-input exposures [20]. Surface-water monitoring studies also reveal that sites receiving multiple pesticides exhibit mixture ratios associated with potential ecological risk even when most individual compounds are classified as low risk [21]. Despite these findings, mixture-based assessments remain limited in low- and middle-income regions, including Eastern Africa, where routine programs typically focus on single-compound analyses rather than integrated exposure scenarios.

The problem is further compounded by the dominance of arid and semi-arid lands (ASALs) in Eastern Africa. Approximately 82% of Kenya's land area is classified as arid or semi-arid [22,23], while over 60% of Ethiopia's land [24] and more than 50% of Tanzania's land [25,26] fall within ASAL zones. These regions are characterized by erratic rainfall patterns and frequent droughts [27,28], prompting increased reliance on irrigation to sustain agricultural production. Irrigation expansion, particularly where flood or furrow systems are used without adequate drainage management, can enhance nutrient leaching and pesticide mobilization into adjacent water bodies [29,30]. Sediment-bound transport pathways are also significant in erosion-prone catchments, facilitating downstream redistribution of adsorbed contaminants [31,32].

Several localized studies have documented pesticide and nutrient contamination in key water bodies within Eastern Africa, including Lake Victoria, Lake Naivasha, and the

Nyando River Basin [1,9,33]. However, these investigations are often site-specific and fragmented, limiting their utility for understanding regional-scale trends and cumulative impacts. In addition, many studies do not explicitly isolate smallholder agricultural contributions from other sources such as urban wastewater, industrial discharge, or large-scale commercial farms, creating attribution uncertainty when interpreting impacts at basin scale.

Despite the growing body of empirical research, there is currently no comprehensive regional synthesis that integrates pesticide and nutrient contamination data across Eastern African countries while critically evaluating ecological and human health implications, methodological limitations, and evidence gaps. A systematic assessment is therefore necessary to consolidate existing findings, examine patterns of contamination, identify drivers and uncertainties, and clarify the strength of evidence linking smallholder agricultural practices to observed surface-water degradation.

Accordingly, this study aims to examine the impact of pesticide and nutrient losses from smallholder agriculture on surface water quality in Eastern Africa. Specifically, it seeks to characterize the quality of surface water in the region with respect to pesticide and nutrient contamination levels; assess the extent of water quality degradation and the associated ecological and human health risks linked to pesticide and nutrient runoff; evaluate methodological approaches used across studies and identify key agricultural practices and environmental factors contributing to surface water pollution. By synthesizing existing research, this review aims to advance understanding of cumulative agrochemical impacts in smallholder systems and support evidence-based water resource governance in Eastern Africa. It provides the first regional synthesis integrating evidence on pesticide contamination, nutrient enrichment, ecological responses, and mitigation practices across Eastern African smallholder agricultural systems.

2. Materials and Methods

2.1. Research Design

We conducted a systematic review and quantitative synthesis of published studies assessing pesticide and nutrient contamination in surface waters across Eastern Africa. This approach integrated findings from multiple independent studies to identify regional contamination trends, quantify overall pollutant levels, and assess heterogeneity across studies. The methodology followed the PRISMA 2020 framework for systematic reviews, encompassing literature search, screening, data extraction, synthesis, and risk of bias evaluation [34]. A review protocol was developed a priori in accordance with PRISMA 2020 guidelines to define the review questions, eligibility criteria, and analytical approach before literature screening commenced.

A completed PRISMA 2020 checklist is provided as Supplementary Table S1.

2.2. Literature Search Strategy

A comprehensive systematic search was conducted across six academic databases: Scopus, Web of Science, PubMed, ScienceDirect, SpringerLink, and Google Scholar. Searches were performed between March and May 2024. In line with PRISMA guidelines, two distinct search strings were developed, one for pesticides and one for nutrients, and each was applied consistently across all databases, with only minor syntax adjustments to meet database requirements.

The search string for pesticides was:

(pesticide OR herbicide) AND (runoff OR loss OR erosion) AND ("smallholder" OR "small-scale") AND (farming OR agriculture) AND ("water quality") AND ("Eastern

https://doi.org/10.3390/pollutants6020032

Africa" OR Kenya OR Tanzania OR Uganda OR Ethiopia OR Rwanda OR Burundi OR "DRC Congo").

The search string for nutrient losses was:

(nutrient AND (runoff OR loss OR erosion)) AND ("smallholder" OR "small-scale") AND (farming OR agriculture) AND ("water quality") AND ("Eastern Africa" OR Kenya OR Tanzania OR Uganda OR Ethiopia OR Rwanda OR Burundi OR "DRC Congo").

The term "pesticide" was used as a general descriptor to capture multiple pesticide classes (including insecticides, herbicides, and fungicides) reported in surface-water studies. During screening and data extraction, individual pesticide compounds were recorded and subsequently grouped by chemical class during synthesis. Although broader agricultural terms were included to capture all relevant studies, screening ensured that only studies where smallholder agriculture was the dominant land use were retained for synthesis. Basin-scale studies with mixed sources (e.g., urban wastewater, industrial effluent, commercial farms) were flagged and treated as contextual evidence rather than direct attribution to smallholders.

For the purposes of this review, Eastern Africa refers to East Africa (Kenya, Uganda, and Tanzania) together with Ethiopia, South Sudan, Rwanda, Burundi, and Somalia, reflecting the IGAD regional grouping and its extensions.

The search strategy was pre-specified and documented in accordance with the PRISMA 2020 protocol, ensuring transparency and reproducibility. Reference lists of retrieved articles were also manually screened to identify further relevant studies. Searches were restricted to peer-reviewed journal articles published between 2010 and 2024.

2.3. Inclusion and Exclusion Criteria

Eligibility parameters were established a priori in accordance with PRISMA 2020 guidelines. Studies were assessed against predefined inclusion and exclusion criteria to ensure relevance, methodological rigor, and consistency across the synthesis. Eligible studies were required to (i) report empirical data on pesticide and/or nutrient contamination of surface waters, (ii) focus on Eastern African catchments, and (iii) be published in peer-reviewed journals between 2010 and 2024. Studies were included where smallholder agriculture was explicitly identified as a dominant land-use activity within the study area or where agricultural runoff was described as a primary contributor to observed surface-water contamination. For basin-scale studies (e.g., Lake Victoria, Lake Naivasha, Nyando River), where multiple pollution sources co-occur, these were included as mixed-source evidence. Attribution to smallholder farming in such contexts remains uncertain and was treated cautiously during synthesis. Studies were excluded if they focused solely on groundwater, laboratory experiments, modeling without validation, or lacked quantitative water quality data. Where catchments included multiple potential pollution sources (e.g., urban wastewater or industrial discharge), such sources were recorded during data extraction (Supplementary Table S3) and considered qualitatively during interpretation.

The full inclusion and exclusion criteria applied during screening are provided in Supplementary Table S2.

2.4. Study Selection

Searches retrieved a total of 644 records: 554 from Google Scholar, 33 from Scopus, and 57 from Web of Science, PubMed, ScienceDirect, SpringerLink combined. Duplicate removal (conducted using Microsoft Excel 2019 (Microsoft Corporation, Redmond, WA, USA) and manual verification) resulted in 362 unique records. Title and abstract screening excluded 285 studies for irrelevance, leaving 77 full-text articles assessed for eligibility. Of these, 36 did not meet inclusion criteria, and 6 were inaccessible, resulting in 35 studies included in the final qualitative and quantitative synthesis. Screening was conducted independently by two authors, with disagreements resolved through discussion and consensus. The PRISMA flow of study selection is summarized in Figure 1, which was generated using R version 4.3.2 (R Foundation for Statistical Computing, Vienna, Austria).

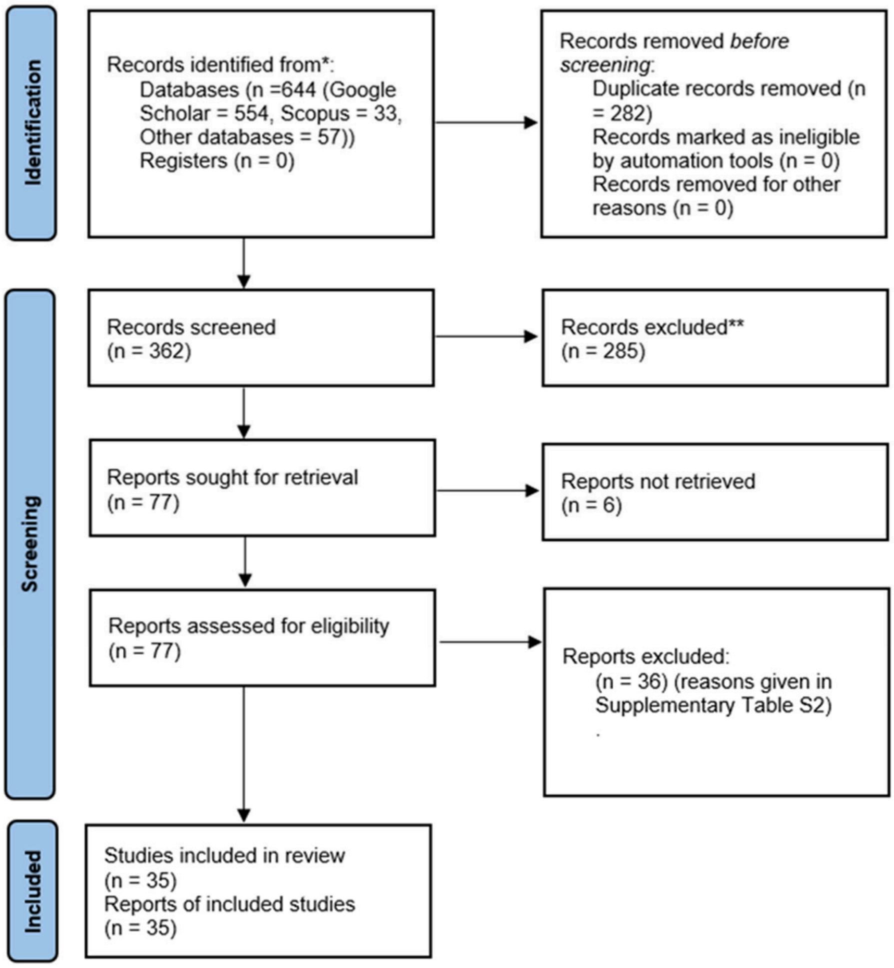

Figure 1. PRISMA flow diagram summarizing study selection process. * Records identified from databases. ** Reasons for exclusion are provided in Supplementary Table S2.

2.5. Data Extraction and Coding

A structured data extraction form was developed to systematically capture key variables from each study. Two authors independently extracted data on study characteristics, water quality parameters, potential pollution sources (including agricultural runoff, urban wastewater, and industrial discharge), and reported ecological impacts. Discrepancies were resolved through discussion to ensure consistency. Where essential data were missing, attempts were made to contact authors; otherwise, such studies were excluded from the quantitative pooling. Where studies reported statistical relationships between agrochemical concentrations and ecological indicators (e.g., chlorophyll-a), correlation coefficients and associated statistics were extracted for comparative synthesis. Some studies reported several relevant variables (e.g., pesticide residues, nutrients, and ecological indicators). As a result, the same studies may contribute data to multiple tables summarizing different outcomes. The categories and specific variables systematically extracted and coded from all included studies are provided in Supplementary Table S3.

2.6. Quantitative Synthesis Approach

Extracted quantitative data were synthesized to summarize reported pesticide and nutrient concentrations, detection frequencies, and study-level associations across the region. Because of substantial heterogeneity in study designs, analytical methods, temporal coverage, and reporting formats, no formal meta-analysis was conducted. In particular, we did not apply inverse variance weighting or random effects modeling, and therefore we avoided presenting pooled averages or regional means that could imply statistical precision.

Instead, all quantitative results are presented descriptively. Reported values are expressed as ranges (minimum–maximum) to capture variability across studies. When multiple studies investigated the same water body within overlapping timeframes, data were synthesized at the waterbody/sub-basin level rather than treating each publication as an independent data point. This approach reduces pseudo-replication and ensures that repeated measurements of the same environmental condition are not double-counted. In addition, for farming system comparisons, categories were defined according to the descriptions provided in the original studies. "Conventional farming" encompassed practices ranging from smallholder maize plots with moderate fertilizer/pesticide use to high-input irrigated horticulture. "Low-input farming" referred to systems with reduced or no synthetic inputs, often incorporating conservation practices or organic amendments. These definitions were applied consistently when grouping studies for descriptive contrasts. Where studies reported concentrations rather than fluxes, values were converted using documented runoff coefficients or soil partitioning factors. These derived values are presented as indicative ranges, not direct measurements.

By focusing on ranges, detection frequencies, and qualitative patterns, our synthesis highlights variability across sites and seasons while remaining consistent with systematic review methodology. This descriptive approach avoids mathematical error, accounts for differences in study design, and provides a transparent representation of agrochemical contamination in Eastern African surface waters. In addition to comparisons with drinking water standards (EU/WHO), reported concentrations were also evaluated against ecological benchmarks, including Environmental Quality Standards (EQSs) and Predicted No-Effect Concentrations (PNECs), where available. These thresholds are derived from ecotoxicological data and represent concentrations below which adverse effects on aquatic organisms are not expected. Incorporating EQS/PNEC values allowed us to distinguish between risks to human health and risks to aquatic ecosystems, thereby strengthening the ecological relevance of our synthesis.

2.7. Quality Assessment and Risk of Bias

Methodological quality was evaluated during data extraction based on reporting transparency, sampling design, analytical methods, temporal coverage, and clarity of outcome measurement. These characteristics were documented using the structured extraction framework (Supplementary Table S3) and considered during interpretation of findings.

Two authors independently reviewed study characteristics and resolved discrepancies through discussion. Studies with limited sampling duration, unclear analytical procedures, or incomplete reporting were interpreted cautiously. Where essential statistical parameters were unavailable, such studies were excluded from quantitative pooling but retained in qualitative synthesis.

Sensitivity analyses were conducted to assess whether exclusion of studies with limited methodological detail materially influenced pooled estimates.

https://doi.org/10.3390/pollutants6020032

2.8. Data Harmonization and Quantitative Data Synthesis

To enable comparison across studies with heterogeneous reporting formats, pesticide and nutrient concentrations were harmonized to common units (µg L^{-1} for pesticides and mg L^{-1} for nutrients). Where necessary, reported values were converted to these standard units prior to synthesis.

Because studies differed substantially in sampling design, analytical methods, temporal coverage, and reporting formats, quantitative synthesis focused on summarizing reported concentration ranges, detection frequencies, and study-level statistics rather than calculating pooled effect sizes. These summaries allowed identification of regional patterns in agrochemical contamination while preserving the variability present across individual studies.

2.9. Sensitivity Considerations

Variability in study design, analytical methods, and sampling coverage was considered during interpretation of results. Because the synthesis relied on reported statistics rather than pooled effect-size models, emphasis was placed on identifying consistent patterns across multiple independent studies rather than relying on individual estimates.

3. Results

3.1. Characteristics of Included Studies

A total of 35 studies met the inclusion criteria under PRISMA guidelines and were included in the final synthesis. These studies, published between 2010 and 2024, represent recent research conducted within the region. By country, most studies were conducted in Kenya (10), Ethiopia (8), Tanzania (7), Uganda (6), Rwanda (2), and Eastern Africa Region (2) (Figure 2). Of the 35 studies, 13 were plot-scale or sub-basin investigations with clearer attribution to smallholder farming, while 22 were basin-scale studies where multiple pollution sources co-occurred. These categories are distinguished in Supplementary Table S4. Where multiple studies reported on the same water body (e.g., Nyando River, Lake Naivasha), values were presented as ranges to avoid artificially weighting heavily studied sites; the Supplementary Table S4 indicates which studies were consolidated under each water body. The geographic distribution of study sites is provided in Supplementary Figure S2. Because of the high number of sites and labels, only basin-scale sites are labelled in the figure. Collectively, these studies provided quantitative data on pesticide and nutrient contamination in surface waters, alongside ecological impacts and contextual factors at watershed and plot levels in arid and semi-arid environments. Because many studies reported multiple water-quality indicators (e.g., pesticide residues, nutrient concentrations, and ecological responses), individual studies contributed data to more than one summary table.

Regarding research themes, pesticide contamination was the most frequently represented topic, appearing in 21 studies, followed by nutrient pollution in 18 studies. However, the depth and distribution of data were uneven: pesticide studies provided more extensive datasets and methodological detail, whereas nutrient studies were fewer and less comprehensive. Far fewer studies explicitly addressed health and socio-economic impacts (3 studies), as reported in Supplementary Table S4.

Additional descriptive figures on publication trends are provided in Supplementary Figure S1.

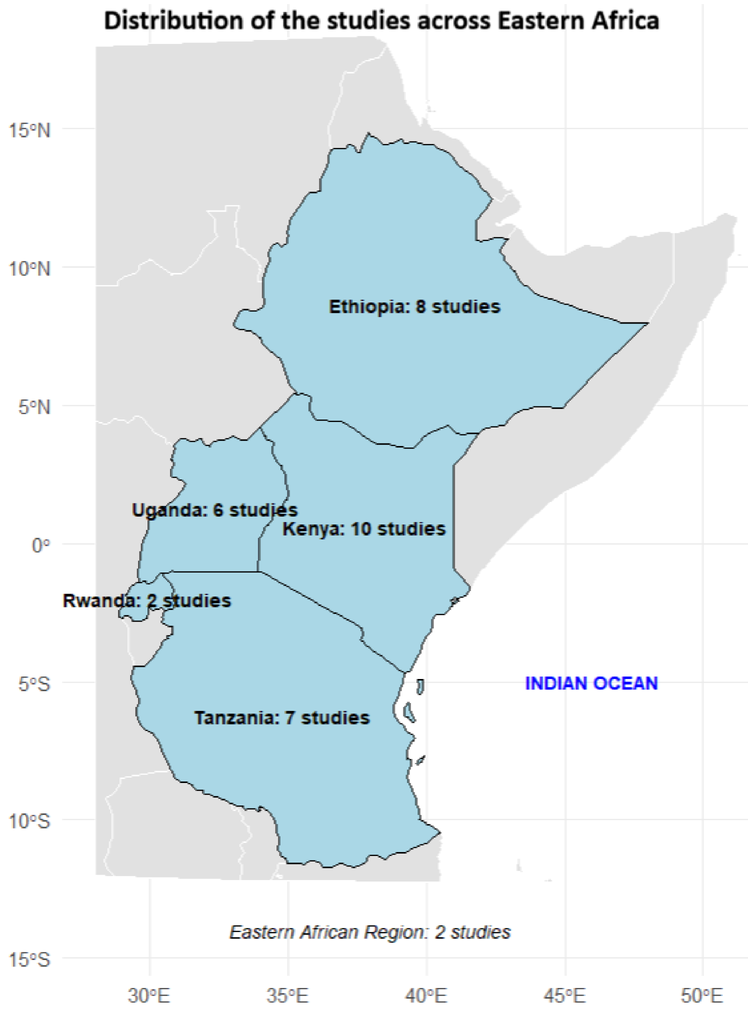

Figure 2. Distribution of the 35 studies across Eastern Africa. Light blue shading refers to countries included in the final synthesis, grey shading refers to other Eastern African countries shown for geographic context.

3.2. Pesticide Contamination

3.2.1. Frequency and Concentrations

Pesticides have been detected in multiple surface-water environments across Eastern Africa, including major lake basins and their inflowing river systems. Evidence from monitoring studies indicates the presence of both legacy organochlorine compounds and a wider spectrum of contemporary pesticide residues in aquatic environments influenced by agricultural activity [35–39].

The range of pesticide concentrations extracted from the reviewed monitoring studies indicate that pesticide contamination is widespread across several major Eastern African surface-water systems. When compared against the European Union Drinking Water Directive parametric value for individual pesticides (0.1 μg L^{-1}), the range of concentrations reported in several key water bodies exceeded this reference benchmark. Reported pesticide concentrations in the Nyando River ranged between 0.27 and 0.55 μg L^{-1}, exceeding the EU Drinking Water Directive benchmark of 0.1 μg L^{-1}. Lake Victoria showed reported values between 0.23 and 0.47 μg L^{-1}, while Lake Naivasha ranged from 0.20 to 0.38 μg L^{-1}. Reported ranges of pesticide concentrations extracted from the reviewed studies for selected water bodies are summarized in Table 1. The reported values represent concentrations of pesticides detected in surface waters, as reported in individual monitoring studies. In addition to drinking water standards, ecological thresholds were considered.

The European Union Environmental Quality Standard (EQS) for individual pesticides is typically 0.01–0.1 μg L^{-1}, while Predicted No-Effect Concentrations (PNEC) for highly toxic compounds such as cypermethrin are often <0.001 μg L^{-1}. Reported concentrations in the Nyando River (0.27–0.55 μg L^{-1}), Lake Victoria (0.23–0.47 μg L^{-1}), and Lake Naivasha (0.20–0.38 μg L^{-1}) exceeded both EQS and PNEC values, indicating ecological risks to aquatic organisms.

Table 1. Reported ranges of pesticide concentrations in selected Eastern African surface waters compared with the EU Drinking Water Directive benchmark (0.1 μg L^{-1}) and evaluated against EQS/PNEC thresholds.

Water Body	Reported Range (μg L^{-1})	Exceeds EU Drinking Water Directive Benchmark	Exceeds EQS/PNEC Thresholds
Nyando River	0.27–0.55	Yes	Yes
Lake Victoria	0.23–0.47	Yes	Yes
Lake Naivasha	0.20–0.38	Yes	Yes

Within the Lake Naivasha catchment, pesticide monitoring has documented the occurrence of organochlorine residues in surface waters and associated sediments. Passive-sampling investigations reported the presence of persistent pesticide compounds across sampling locations within the basin, indicating ongoing environmental persistence and transport within connected river–lake systems [40]. Additional monitoring within the catchment has also identified multiple pesticide compounds through broad-spectrum screening approaches, demonstrating that multi-residue analytical techniques can reveal a wider diversity of pesticide contamination than targeted legacy-compound analyses [20].

Across the wider Lake Victoria basin, pesticide contamination has been reported in both tributary rivers and near-shore aquatic environments. Monitoring of inflow systems such as the Kibos–Nyamasaria River has identified organochlorine pesticide residues in water and sediment samples across seasons [41]. Studies conducted within connected Kenyan catchments, including the Nyando River drainage basin, similarly report pesticide residues in environmental matrices such as water, sediments, and aquatic vegetation, confirming the occurrence of pesticide contamination in tributaries feeding the lake [42]. Basin-wide monitoring studies further report the presence of diverse organic micropollutants, including pesticide compounds, in freshwater systems associated with the Lake Victoria basin [36].

Beyond Kenya, pesticide monitoring studies in other Eastern African aquatic systems also report contamination in surface waters associated with agricultural landscapes. Investigations in Tanzanian river basins have detected organohalogen pesticide residues in surface waters and sediments [35], while monitoring studies in Ugandan agricultural catchments have identified multiple pesticide compounds in surface waters using passive-sampling approaches [37]. Similar findings have been reported in Ethiopian watersheds, where agricultural pesticide residues have been detected in surface-water systems influenced by farming activities [38,39].

More evidence of pesticide occurrence across the reviewed Eastern African water bodies/catchments is summarized in Supplementary Table S5.

3.2.2. Types of Pesticides Detected

The most frequently detected pesticide groups were organochlorines (e.g., DDT), organophosphates (e.g., malathion), pyrethroids (e.g., cypermethrin), and selected carbamates (e.g., carbofuran) [35,37,39,41,43]. Across the reviewed literature, DDT was reported in 18 of the 23 studies assessing pesticide contamination (78%). Given that agricultural use of DDT has been banned, these detections are most likely attributable to legacy residues and illegal indoor residual spraying for malaria control, rather than current smallholder

https://doi.org/10.3390/pollutants6020032

agricultural intensification. This highlights the need to differentiate legacy POPs from current-use pesticides (CUPs) when interpreting contamination patterns. The distribution of frequently reported pesticide groups and their associated ecosystems is summarized in Table 2.

Table 2. Most common pesticides and affected ecosystems (from the 21 studies).

Pesticide Type	Detection (%)	Primary Locations	Risk Level
DDT (OC)	78%	Lake Victoria, Nyando	Very High
Cypermethrin	72%	Naivasha, Hawassa	High
Malathion	67%	Lake Victoria, Nyando	Medium

3.2.3. Bioaccumulation in Fish

Pesticide bioaccumulation in commonly consumed fish species has been reported in several studies across Eastern African aquatic systems [35,43–45]. In some cases, reported concentrations exceeded applicable FAO/WHO maximum residue limits (MRLs). For example, African catfish from Lake Victoria exhibited pesticide concentrations ranging between 2.1 and 2.8 μg kg^{-1}, consistently exceeding the FAO/WHO maximum residue limit (MRL) of 1.2 μg kg^{-1}. Nile tilapia showed reported values between 1.5 and 2.0 μg kg^{-1}, while silver cyprinid ranged from 1.2 to 1.5 μg kg^{-1}. Reported concentrations in fish tissues across the reviewed studies are summarized in Table 3.

Table 3. Reported range of pesticide concentrations in fish tissues.

Fish Species	Reported Range (μg kg^{-1})	FAO/WHO MRL (μg kg^{-1})	Exceeds MRL
Nile Tilapia (*Oreochromis niloticus*)	1.5–2.0	1.0	Yes
African Catfish (*Clarias gariepinus*)	2.1–2.8	1.2	Yes
Silver Cyprinid (*Rastrineobola argentea*)	1.2–1.5	1.0	Yes

3.2.4. Associations Between Pesticide Use and Aquatic Ecosystem Indicators

Across the reviewed studies, several authors reported associations between agricultural pesticide use and indicators of aquatic ecosystem degradation. Monitoring studies conducted in agricultural catchments consistently identified pesticide residues in surface waters draining intensively farmed landscapes, suggesting that agricultural inputs contribute to contamination of freshwater systems in Eastern Africa [37,38,40,42]. A summary of study-reported associations between pesticide inputs and ecosystem indicators is provided in Supplementary Table S6.

In the Lake Naivasha catchment, pesticide residues have been detected in surface waters and sediments associated with agricultural activities surrounding the lake, indicating that pesticide transport from cultivated areas may influence water quality within the basin [1,40]. Similar observations have been reported in tributary systems of the Lake Victoria basin, where pesticide residues have been detected in riverine inflows such as the Nyando River and the Kibos–Nyamasaria River, supporting the role of agricultural runoff in transporting pesticide contaminants into downstream aquatic ecosystems [41,42].

Beyond Kenya, evidence from monitoring studies in Tanzanian and Ugandan catchments similarly indicates that pesticide contamination occurs in surface waters associated with agricultural landscapes. For example, monitoring of rural river basins in Tanzania detected organohalogen pesticide residues in surface waters and sediments, reflecting diffuse agricultural inputs to aquatic environments [35]. In Ugandan agricultural catchments, passive-sampling investigations have identified multiple pesticide compounds in surface waters, demonstrating the presence of complex pesticide mixtures in freshwater systems influenced by farming activities [37].

Although many of the reviewed studies did not quantify statistical relationships between pesticide application intensity and ecological indicators, several reported evidence of ecological impacts associated with pesticide contamination. These impacts include reduced water quality, increased contaminant loads in aquatic sediments, and potential effects on aquatic biota such as fish and plankton communities [2,46,47]. Collectively, these findings suggest that intensive agricultural practices and pesticide use contribute to the degradation of freshwater ecosystems across Eastern Africa.

3.2.5. Seasonal Variability in Pesticide Concentrations

Several monitoring studies reported seasonal variation in pesticide concentrations in surface waters across Eastern African agricultural catchments. In many cases, higher pesticide concentrations were detected during rainy periods compared with dry seasons.

For example, monitoring studies conducted in Tanzanian agricultural watersheds reported increased concentrations of organophosphate pesticides during wet seasons. The range of concentrations increased from approximately 0.25 μg L^{-1} during dry periods to 0.35 μg L^{-1} during rainy periods, reflecting increased transport of pesticides from agricultural fields to adjacent water bodies following rainfall events [17].

Similar seasonal patterns have been reported in other Eastern African agricultural systems. In the Lake Naivasha basin, pesticide monitoring using passive samplers indicated higher pesticide detection frequencies and concentrations during rainy periods compared with dry seasons, suggesting rainfall-driven mobilization of agricultural chemicals within the catchment [40].

Seasonal differences in pesticide occurrence have also been documented in agricultural water bodies in Kenya and Uganda. Studies examining pesticide residues in aquaculture ponds and surface waters in Kenya reported higher pesticide detections during periods of increased rainfall and agricultural activity [45]. Evidence from Ugandan agricultural catchments similarly indicates seasonal fluctuations in water quality linked to runoff from cultivated landscapes [48,49].

3.3. Nutrient Losses and Surface Water Quality

3.3.1. Nitrogen and Phosphorus Concentrations

Across 14 studies, nitrate (NO_3^-) and phosphate (PO_4^{3-}) concentrations were reported for major surface-water bodies in Eastern Africa. Nitrate concentrations across sites ranged between 0.99 and 4.1 mg L^{-1}, remaining below the WHO guideline of 50 mg L^{-1}. Phosphate concentrations varied more widely, from 0.16 to 1.9 mg L^{-1}, with several sites exceeding eutrophication benchmarks (0.1 mg L^{-1}). For example, Lake Mulehe reported values between 0.6 and 2.0 mg L^{-1}, while Nyakomisaro-Riana ranged from 0.16 to 0.34 mg L^{-1}. Ecological thresholds for nutrients include ~2 mg L^{-1} for nitrate and ~0.1 mg L^{-1} for phosphate to protect against eutrophication. Reported nitrate concentrations (up to 5.6 mg L^{-1} in the Nyando River) and phosphate concentrations (up to 2.0 mg L^{-1} in Lake Mulehe) exceeded these ecological benchmarks, confirming risks of algal blooms and aquatic ecosystem degradation (Table 4).

Table 4. Reported range of nutrient concentrations.

Water Body	Reported NO_3^- Range (mg L^{-1})	Reported PO_4^{3-} Range (mg L^{-1})	Exceeds EU Drinking Water Directive Benchmark	Exceeds EQS/ PNEC Thresholds
Lake Victoria	2.1–4.3	0.56–1.0	Yes	Yes
Nyando River	2.6–5.6	0.73–1.3	Yes	Yes
Lake Naivasha	1.9–3.7	0.47–0.83	Yes	Yes
Lake Mulehe	2.9–3.2	0.6–2.0	Yes	Yes
Nyakomisaro-Riana	0.99–1.4	0.16–0.34	Yes	Yes (PO_4^{3-})

https://doi.org/10.3390/pollutants6020032

3.3.2. Seasonal Variability in Nutrient Concentrations

Nutrient concentrations peaked during rainy seasons; phosphorus concentrations ranged from 0.27 to 0.49 mg L^{-1} in the dry season and from 0.77 to 1.33 mg L^{-1} in the rainy season, representing an approximate 79% increase. Nitrate concentrations showed similar seasonal increases, with dry-season values between 1.7 and 3.1 mg L^{-1} compared to 3.1–5.5 mg L^{-1} in the rainy season. The majority of studies relied on grab sampling approaches, which may underestimate peak concentrations associated with short-duration storm events. Seasonal nutrient concentrations reported across the reviewed studies, such as Nsanzabaganwa et al. [50], Mng'ong'o et al. [51], and Ogendi [52], are summarized in Table 5.

Table 5. Seasonal nutrient concentrations reported in Eastern African catchments.

Season	NO_3^- Concentration Range (mg L^{-1})	PO_4^{3-} Concentration Range (mg L^{-1})	Increase from Dry Season (%)
Dry Season	1.7–3.1	0.27–0.49	—
Rainy Season	3.1–5.5	0.77–1.33	79%

The studies documented elevated phosphorus concentrations in agricultural and peri-urban catchments [53–55]; however, long-term standardized monitoring datasets across the region were limited.

3.3.3. Eutrophication, Cyanobacteria and Aquatic Biodiversity

Nutrient Enrichment and Algal Blooms

Positive associations between phosphorus concentrations and chlorophyll-a were reported across multiple sites. Reported chlorophyll-a concentrations ranged between 30.6 and 40.2 μg L^{-1} in Lake Victoria, 36.0 and 48.2 μg L^{-1} in the Nyando River, and 28.6 and 37.2 μg L^{-1} in Lake Naivasha. Phosphorus concentrations varied between 0.56 and 1.00 mg L^{-1}, 0.73 and 1.31 mg L^{-1}, and 0.47 and 0.83 mg L^{-1} respectively [47,50,52]. Study-level Pearson correlation coefficients remained strong ($r = 0.79$–0.85), indicating consistent associations despite variability in reported values (Table 6).

Table 6. Correlation of phosphorus with algal biomass (chlorophyll-a).

Water Body	Reported Chlorophyll-a Range (μg L^{-1})	Reported PO_4^{3-} Range (mg L^{-1})	Correlation (r)
Lake Victoria	30.6–40.2	0.56–1.00	0.82
Nyando River	36.0–48.2	0.73–1.31	0.85
Lake Naivasha	28.6–37.2	0.47–0.83	0.79

These coefficients represent study-specific correlation analyses extracted from the respective primary sources.

Cyanobacteria Blooms and Toxin Production

Microcystin concentrations from cyanobacterial blooms exceeded WHO provisional drinking water guideline value (1 μg L^{-1}) in multiple reported systems. Reported microcystin concentrations from cyanobacterial blooms exceeded the WHO provisional drinking-water guideline value (1 μg L^{-1}) in multiple systems. In Lake Victoria, reported values ranged between 1.43 and 2.91 μg L^{-1}; in the Nyando River, between 2.07 and 3.71 μg L^{-1}; and in Lake Manyara, between 5.92 and 6.17 μg L^{-1}. These ranges across sites obtained from monitoring studies, including Ogendi [52] and Simiyu et al. [47], are summarized in Table 7.

Table 7. Microcystin concentrations across key water bodies.

Water Body	Reported Microcystin Range (μg L^{-1})	WHO Guideline (μg L^{-1})
Lake Victoria	1.43–2.91	1.0
Nyando River	2.07–3.71	1.0
Lake Manyara	5.92–6.17	1.0

Decline in Fish Populations

The included studies documented declines in fisheries-related indicators, including Catch per Unit Effort (CPUE), biomass estimates, and annual landings in selected systems. Reported declines ranged from 29% to 42% across study-specific assessment periods within 2010–2024. An example reported in the literature include declines in CPUE in Lake Victoria and reduced biomass in Lake Tana. Reported fisheries indicators are summarized in Table 8 based on studies such as Dejen et al. [56] and Makgoba et al. [44].

Table 8. Reported declines in fisheries indicators.

Water Body	Reported Change	Metric
Lake Victoria	~35% decline	CPUE
Nyando River	~42% decline	Abundance indices
Lake Tana	~35% decline	Biomass (kg ha^{-1})

These declines occurred in systems where elevated nutrient concentrations and bloom events were also documented; however, the respective studies noted multiple contributing stressors such as eutrophication, oxygen depletion and toxic cyanobacteria blooms.

3.4. Influence of Farming Practices and Mitigation Measures

3.4.1. Farming System Type (Conventional vs. Organic)

Across the reviewed literature, agricultural systems characterized by higher pesticide inputs reported greater estimated runoff losses than systems using lower-input or organic management practices, while nutrient inputs were generally modest and less frequently exceeded ecological thresholds. Reported pesticide runoff in conventional farming systems ranged between 1.3 and 2.9 kg ha^{-1} $year^{-1}$, while organic or reduced-input systems reported values between 0.3 and 0.7 kg ha^{-1} $year^{-1}$. Nitrogen losses varied from 28.8 to 47.6 kg ha^{-1} $year^{-1}$ in conventional systems compared with 10.1 to 21.5 kg ha^{-1} $year^{-1}$ in lower-input systems. Phosphorus runoff showed similar differences, ranging from 6.5 to 12.7 kg ha^{-1} $year^{-1}$ in conventional systems compared with 2.2 to 4.6 kg ha^{-1} $year^{-1}$ in organic systems. These ranges reflect independent studies conducted across different sites and contexts such as studies by Mahugija et al. [43], Makgoba et al. [44], and Oltramare et al. [37], and are summarized in Table 9, illustrating consistent differences in runoff while acknowledging heterogeneity in farming practices. Values in the table include directly reported fluxes and conversions from soil/sediment concentrations using published coefficients. These ranges are intended to illustrate variability across systems.

Table 9. Reported ranges of agrochemical runoff estimates for conventional and organic/low-input farming systems in Eastern African catchments.

Farming System	Pesticide Runoff Range (kg ha^{-1} yr^{-1})	Nitrogen Runoff Range (kg ha^{-1} yr^{-1})	Phosphorus Runoff Range (kg ha^{-1} yr^{-1})
Conventional Farming	1.3–2.9	28.8–47.6	6.5–12.7
Organic/Lower-Input Farming	0.3–0.7	10.1–21.5	2.2–4.6

Fertilizer and Pesticides Application Methods and Irrigation Practices

Differences in fertilizer and pesticide application methods, together with irrigation practices, were consistently associated with variation in reported agrochemical losses across the reviewed studies. Among commonly reported pesticide application methods, broadcast spraying was associated with relatively high pesticide losses, with the range of losses averaging approximately 18.2% of the applied pesticide amount. Even higher losses were reported under aerial spraying systems, where reported pesticide losses reached approximately 25.5% of the applied amount [2,46,57]. Across the reviewed studies, these application methods were repeatedly associated with greater off-target movement and higher variability in reported pesticide losses compared with more controlled application approaches.

In contrast, controlled delivery systems generally reported substantially lower pesticide losses. Drip irrigation systems were associated with comparatively low pesticide losses, averaging approximately 4.8% of the applied pesticide amount, while precision application techniques, such as targeted or sensor-based pesticide delivery, were associated with the lowest reported losses, averaging approximately 2.9% of applied pesticides [37,38]. Overall, studies consistently showed a gradient of decreasing pesticide losses from conventional broadcast and aerial spraying methods toward more targeted application technologies.

Similar patterns were observed for nutrient losses. Conventional furrow irrigation systems were associated with relatively high nitrogen losses, with studies reporting the range of nutrient losses of approximately 28.7% of applied fertilizer. In comparison, drip irrigation systems were associated with lower nutrient losses (approximately 11.2%), while precision fertilizer application methods reported the lowest losses (approximately 7.4% of applied fertilizer). These findings suggest that improved irrigation management and targeted agrochemical application techniques may substantially reduce nutrient and pesticide losses from agricultural systems [48,58,59]. Across studies, nutrient losses generally declined under irrigation and fertilizer application systems designed to improve input placement efficiency and reduce excess water movement.

Reported estimates of agrochemical losses associated with different applications and irrigation practices are summarized in Supplementary Table S7.

Crop Types and Input Intensity

Crop type was associated with substantial variation in agrochemical input intensity and reported runoff losses across agricultural systems in Eastern Africa [2,43,46,50,57]. Horticultural cropping systems consistently reported higher pesticide and fertilizer application rates than cereal-based systems. Synthesis of input data reported across these studies indicates that horticultural crops such as tomatoes and cabbage typically required between 4.2 and 5.4 kg ha^{-1} yr^{-1} of pesticides and 110–130 kg ha^{-1} yr^{-1} of fertilizers, whereas millet production systems were associated with lower agrochemical inputs ranging from 0.6 to 1.0 kg ha^{-1} yr^{-1} of pesticides and 39–46 kg ha^{-1} yr^{-1} of fertilizers.

Intermediate agrochemical input levels were observed for crops such as maize, rice, and coffee production systems, reflecting variability in nutrient demand and pest management intensity among cropping systems [4,48,59]. Across the reviewed studies, horticultural systems generally represented the most input-intensive production systems, whereas cereal-based systems tended to report comparatively lower agrochemical use levels. Differences in reported agrochemical input intensity by crop type are summarized in Supplementary Table S8.

https://doi.org/10.3390/pollutants6020032

3.4.2. Mitigation Practices

Buffer Strips and Cover Cropping

Vegetated buffer strips and cover cropping were reported to reduce nutrient and pesticide runoff in multiple studies. Nsanzabaganwa et al. [50] reported that riparian buffer strips in Rwanda's Nyabarongo catchment reduced nitrogen runoff by 25–40% and phosphorus runoff by 30–45%. Ogendi [52] documented reductions in nitrate concentrations of 0.9–1.4 mg L^{-1} and phosphate concentrations of 0.3–0.6 mg L^{-1} in systems with vegetated riparian zones. At the global scale, Stehle and Schulz [60] reported reductions in pesticide runoff ranging from 40 to 80% under vegetated buffer conditions. Cover cropping, as observed in East African catchments [50,61], was associated with reported nitrogen reductions of approximately 35–50% and phosphorus reductions of approximately 40–50% (Table 10). However, reported mitigation effects varied across studies depending on buffer width, crop system, and local hydrological conditions.

Table 10. Reported mitigation practices and associated reductions in runoff.

Mitigation Practice	Reduction in Pesticide Runoff (%)	Reduction in Nitrogen Runoff (%)	Reduction in Phosphorus Runoff (%)
Buffer Strips (3 m)	40–80%	25–40%	30–45%
Buffer Strips (10 m)	Greater reductions reported than narrower strips	—	—
Cover Cropping	Indirect reductions via runoff control	35–50%	40–50%

Conservation Tillage vs. Conventional Tillage

Conservation tillage practices were generally associated with reduced soil erosion and lower agrochemical transport compared with conventional tillage systems in agricultural landscapes. Studies examining agricultural land management in Eastern African catchments report that reduced soil disturbance and improved soil cover under conservation practices can limit soil erosion and decrease the movement of nutrients and pesticides into surrounding water bodies [46,48,50,58].

Synthesis of reported estimates across the reviewed studies indicates that conservation tillage practices were associated with lower levels of soil erosion and agrochemical runoff relative to conventional tillage systems. Estimated soil erosion declined from 7.5–8.9 to 3.1–3.9 tons ha^{-1} yr^{-1}, pesticide runoff from 1.8–2.4 to 0.6–0.8 kg ha^{-1} yr^{-1}, and nutrient runoff from 32–37 to 16–20 kg ha^{-1} yr^{-1} under conservation management practices. Comparative ranges for tillage practices are provided in Supplementary Table S9.

3.4.3. Seasonal Variations in Agricultural Runoff

Influence of Rainfall Patterns on Runoff

Runoff contamination exhibited pronounced seasonal variation in many of the reviewed studies, with higher contaminant concentrations typically reported during rainy periods when surface runoff and soil erosion increase [4,35,42,47]. Increased rainfall can mobilize pesticides and nutrients from agricultural soils, transporting them into adjacent rivers, lakes, and wetlands.

Across the reviewed monitoring studies, pesticide concentrations were generally higher during rainy periods compared with dry seasons. The synthesis of reported values across the reviewed literature indicate that pesticide concentrations ranged from 0.13 to 0.23 µg L^{-1} during dry periods and from 0.25 to 0.49 µg L^{-1} during rainy periods, reflecting rainfall-driven mobilization. Nitrate concentrations showed similar seasonal increases, ranging from 1.7 to 3.5 mg L^{-1} in dry seasons compared with 3.4 to 6.2 mg L^{-1}

in rainy seasons. Seasonal differences in agrochemical concentrations are summarized in Supplementary Table S10.

3.5. Socioeconomic Factors and Their Influence on Pesticide and Nutrient Management

3.5.1. Farmer Knowledge, Education and Adoption of Best Practices

Farmer education and access to agricultural knowledge were consistently associated with differences in the adoption of best management practices (BMPs) related to pesticide and nutrient use. Studies examining agricultural management in Eastern African farming systems indicate that farmers with higher levels of education or greater access to agricultural extension services are more likely to adopt improved pest and nutrient management strategies, including integrated pest management (IPM), targeted fertilizer application, and soil conservation practices [46,57,62].

Across studies reporting education-stratified data, adoption of best management practices was generally lower among farmers with limited formal education. For example, adoption of integrated pest management was reported at approximately 10% among farmers with minimal formal education, while adoption of precision fertilizer application and vegetative buffer strips was reported at approximately 6% and 4%, respectively. In contrast, substantially higher adoption rates were observed among farmers with higher levels of education, with reported adoption rates of approximately 84% for IPM, 78% for precision fertilizer application, and 68% for vegetative buffer strips.

These findings are consistent with broader evidence indicating that improved farmer education and knowledge of sustainable agricultural practices can enhance the adoption of environmentally beneficial management practices and reduce the risk of agrochemical losses to surrounding water bodies [4,37,38]. Estimates of BMP adoption rates across education categories are summarized in Supplementary Table S11.

3.5.2. Access to Credit, Inputs and Extension Services

Limited financial and institutional capacity was frequently identified as a constraint to the adoption of conservation-oriented agricultural practices in Eastern African farming systems. Several studies reported that adoption of improved nutrient and pesticide management practices is influenced by access to financial resources, agricultural inputs, and advisory services [4,46,57,62,63]. In many smallholder systems, limited capital availability constrains the adoption of improved irrigation systems, soil conservation structures, and alternative nutrient management practices that could reduce runoff losses to surrounding water bodies [48,50,58,64]. Extracted economic comparisons from the reviewed studies suggest that sustainable management practices may reduce long-term production costs. For example, study-reported estimates indicate that annual input costs declined from approximately USD 110 ha^{-1} under conventional management to USD 85 ha^{-1} under organic systems, corresponding to an estimated USD 25 ha^{-1} reduction in annual input costs. However, several studies also note that higher upfront investment requirements for organic fertilizers, improved seed varieties, and soil conservation measures can create barriers to adoption among smallholder farmers [50,57,62].

Advisory systems also influence farmer decisions regarding agrochemical use. Evidence from studies conducted in Uganda and Ethiopia suggests that many farmers rely on private input suppliers or agrochemical dealers for advice on pesticide use rather than formal public extension systems, reflecting limited extension coverage and resource constraints in agricultural advisory services [57,62,65]. Extracted economic comparisons and advisory-system influences on agrochemical management are summarized in Supplementary Table S12.

3.5.3. Market and Price Fluctuations

Input price volatility may also influence agrochemical application decisions in agricultural systems. Extracted values from studies reporting both price and application data suggest that agrochemical price increases can be associated with reductions in application intensity [46,62,63,66]. For example, study-reported values indicate that average agrochemical prices increased from approximately USD 1.10 kg^{-1} in 2015 to USD 2.53 kg^{-1} in 2021, while the range of application rates declined from approximately 95 kg ha^{-1} to 59 kg ha^{-1}, corresponding to an estimated 38% reduction in application intensity [46,62,63,66]. These values represent aggregated estimates derived from studies reporting both price and application data rather than basin-wide measurements.

The reviewed literature also indicates that farmer decisions regarding agrochemical use are shaped by a combination of economic pressures, resource availability, and crop production requirements [57,62]. Fluctuations in the affordability and availability of agricultural inputs may therefore influence pesticide and nutrient use patterns, and indirectly, the risk of agrochemical transport to surrounding water bodies.

3.6. Evidence of Increasing Pesticide and Nutrient Pressures in Water Sources

3.6.1. Pesticide Trends in the Nyando River

Monitoring studies conducted in the Nyando River basin and related Lake Victoria inflow systems indicate persistent pesticide contamination in agricultural catchments influenced by intensive farming activities [36,41,42]. Extracted study-reported pesticide concentrations from monitoring campaigns conducted between 2010 and 2024 suggest increasing concentrations in more recent sampling periods. Based on the reviewed literature, reported pesticide concentrations in the Nyando River increased over time, with earlier monitoring campaigns documenting values between 0.13 and 0.23 µg L^{-1}, while more recent studies reported ranges of 0.31 to 0.47 µg L^{-1}. Although the available studies differ in sampling design and analytical methods, the extracted values collectively suggest sustained pesticide pressures in river systems draining agricultural landscapes within the Lake Victoria basin. Extracted monitoring values are summarized in Supplementary Table S13.

3.6.2. Nutrient and Eutrophication Trends in Lake Victoria

Similarly, nutrient and eutrophication indicators reported in Lake Victoria studies conducted between 2010 and 2024 indicate substantial nutrient enrichment pressures in the basin. Studies examining water quality in Lake Victoria and connected catchments have reported elevated nutrient concentrations and increasing eutrophication indicators in several near-shore and gulf environments [36,42,47,55].

Extracted study-reported phosphorus concentrations in Lake Victoria ranged from 0.22 to 0.46 mg L^{-1} in earlier monitoring studies, increasing to 0.77–1.35 mg L^{-1} in more recent studies. Chlorophyll-a concentrations similarly rose from 16–27 µg L^{-1} to 43–59 µg L^{-1}, reflecting intensifying eutrophication pressures.

Extracted nutrient and eutrophication indicators from the reviewed studies are summarized in Supplementary Table S14.

4. Discussion

4.1. Extent of Pesticide and Nutrient Contamination in Surface Water

This systematic review demonstrates that pesticide and nutrient contamination is widespread across surface water systems in Eastern Africa, with consistent exceedances of both drinking-water and ecological benchmark values in intensively cultivated catchments. Concentrations of pesticide residues, notably organochlorines such as DDT, aldrin, and dieldrin, as well as organophosphates like chlorpyrifos, were frequently found to exceed

https://doi.org/10.3390/pollutants6020032

WHO and FAO recommended thresholds for drinking water safety [2,42,67]. It is important to distinguish between drinking-water guideline values and ecological risk benchmarks; while the former are designed to protect human health, the latter reflect potential impacts on aquatic organisms and ecosystem functioning.

Importantly, contamination levels in several basins not only surpassed drinking-water safety limits but also ecological thresholds (EQS/PNEC). These ecological benchmarks, derived from toxicity data, represent concentrations below which no adverse effects on aquatic organisms are expected. Their exceedance indicates that aquatic ecosystems in Eastern Africa are exposed to levels capable of impairing biodiversity and ecological functioning, highlighting dual risks to human and environmental health. Exceedances were observed relative to both categories in multiple systems. The pattern, however, was uneven: pesticide concentrations frequently surpassed WHO/FAO drinking-water limits and ecological benchmarks, whereas nutrient concentrations, though elevated, were often well below ecological thresholds. This reflects differences in input intensity and compound behavior, with pesticide applications involving persistent and toxic compounds, while fertilizer inputs in many smallholder systems remain comparatively modest. Accordingly, the reference to 'high agrochemical inputs' primarily reflects pesticide contamination rather than nutrient enrichment. Persistent detection of organochlorines across several basins suggests either long-term environmental persistence, remobilization from contaminated sediments, or continued inputs in some areas, consistent with findings from the Nyando River catchment and other East African systems [42,67,68]. While illegal use cannot be ruled out, sediment-bound legacy contamination and slow degradation rates likely contribute substantially to observed concentrations. Accordingly, detections of compounds such as DDT need to be interpreted as legacy persistent organic pollutants (POPs) linked to historical use or non-agricultural applications (e.g., indoor residual spraying for malaria control), whereas current-use pesticides (CUPs) reflect ongoing smallholder practices. This distinction is critical for accurate attribution of contamination sources. The high detection frequencies documented in this review are consistent with global syntheses reporting widespread insecticide contamination in agricultural regions [60], situating Eastern Africa within broader global contamination patterns.

It is also notable that more recent pesticide classes, such as neonicotinoids and systemic fungicides, were not reported in the reviewed studies. This likely reflects both the relatively low rate of adoption among smallholder farmers in Eastern Africa and methodological constraints, as many monitoring programs lack the analytical capacity to detect newer pesticide chemistries. These gaps highlight important regional knowledge limitations and the need for expanded monitoring to capture emerging contaminants. Nutrient enrichment represents a parallel and interacting pressure. Across reviewed studies, nitrate (NO_3^-) and phosphate (PO_4^{3-}) concentrations frequently exceeded eutrophication-related ecological thresholds, and in some cases surpassed drinking-water standards [49,58]. Elevated nutrient levels were most commonly reported in catchments characterized by high fertilizer input intensity, limited buffer zones, and erosion-prone soils. These findings align with broader limnological evidence demonstrating that agricultural intensification without nutrient management controls is a primary driver of freshwater eutrophication globally [69].

Seasonal dynamics further amplify contamination risks. Across multiple studies included in this synthesis, concentrations of pesticides and nutrients increased substantially during rainy seasons, reflecting rainfall-driven mobilization through surface runoff and erosion processes. Beyond seasonal averages, watershed hydrology in Eastern Africa is strongly episodic. Short-duration storm events can generate disproportionately large 'first flushes' of nutrient and pesticide transport at peak flows. Because most studies relied on grab sampling, these episodic peaks may be underestimated, emphasizing the need for event-based sampling designs to fully capture storm-driven variability. Reported increases ranged from 50% to 85% between dry and wet periods in semi-arid systems of Ethiopia, Kenya, Rwanda and Tanzania [38,42,50,52,63,67]. For instance, phosphorus exports to the Nyanza Gulf of Lake Victoria were observed to peak following intense rainfall events [47].

Importantly, these observed seasonal runoff dynamics should be distinguished from longer-term anthropogenically driven climate change. Current contamination pulses are primarily associated with natural monsoonal rainfall cycles and episodic storm hydrology that govern seasonal transport processes across Eastern African catchments. In contrast, climate change projections reported by the IPCC relate to shifts in the frequency, intensity, and temporal distribution of extreme precipitation events, including flash floods, prolonged droughts, and subsequent high-intensity rainfall episodes. Such hydroclimatic changes may alter future agrochemical transport pathways and increase the magnitude, frequency, and spatial extent of contamination events, potentially compounding the vulnerabilities already observed under existing seasonal hydrological regimes.

Nutrient losses from smallholder-dominated agricultural systems are particularly consequential because of the cumulative effect of numerous dispersed farms within shared catchments. Reported phosphorus losses of 5–15 kg ha^{-1} yr^{-1} in Ethiopia's Rift Valley have been associated with downstream eutrophication of Lakes Ziway and Hawassa [4,59]. Similarly, in Kenya's River Nyakomisaro-Riana, downstream increases in phosphorus and nitrate concentrations corresponded with shifts in algal community composition, including increased relative abundance of cyanobacteria such as Microcystis aeruginosa [52]. These site-specific findings illustrate how diffuse nutrient inputs from smallholder systems can translate into measurable ecological responses at basin scale. Because some runoff flux values were derived from soil or sediment concentrations using assumed coefficients, they need to be interpreted cautiously as indicative ranges rather than direct measurements.

Overall, the evidence synthesized in this review indicates that pesticide residues and nutrient enrichment are not isolated occurrences but represent regionally recurrent pressures linked to agricultural intensification, hydrological variability, and management limitations. However, variability in analytical methods, monitoring frequency, and compound coverage across studies highlights the need for standardized long-term surveillance to improve regional risk characterization.

4.2. Drivers of Pesticide and Nutrient Runoff

4.2.1. Agricultural Intensification and Overuse of Agrochemicals

Agricultural expansion and intensification increase the mass of agrochemicals applied within catchments and, consequently, the potential for off-site transport when stewardship measures are limited [11]. At the global scale, FAO statistics indicate that total pesticide use increased by ~13% over the past decade and has approximately doubled since 1990, reflecting broad intensification trends in agricultural input use [60,70]. Within Eastern Africa, the reviewed studies consistently indicate that high-input cropping systems (e.g., irrigated rice and horticulture) and frequent application schedules are associated with higher reported ranges of concentrations in adjacent surface waters, particularly where mixing, calibration, and timing guidance are limited [42]. Poor on-farm practices exacerbate runoff risk through both over-application and higher likelihood of application immediately before rainfall events. For example, surveys in the Nyando basin reported substantial non-compliance with recommended pesticide rates and low use of protective equipment [42], indicating gaps in training and risk management that are relevant to both environmental transport and human exposure pathways. Consistent with this, broader assessments of smallholder nutrient management emphasize that limited extension coverage and weak nutrient stewardship frameworks constrain adoption of best practices and increase the likelihood of nutrient losses to surface waters [70]. Because the majority of farms in Eastern Africa are smallholder systems, cumulative runoff from numerous small fields can generate basin-scale contamination patterns even where individual farms apply relatively modest agrochemical inputs [11,69]. Such practices intensify contamination to levels that exceed both human health guidelines and ecological benchmarks, highlighting the need for improved stewardship to protect communities and aquatic ecosystems. When pesticide or fertilizer applications coincide with storm events, the resulting first flushes can rapidly transport high concentrations into streams, amplifying ecological risks. This further emphasizes the importance of event-based monitoring approaches to capture peak transport episodes.

4.2.2. Land Use Changes and Vegetation Loss

Land use changes, including deforestation, wetland conversion, and riparian encroachment, reduce landscape retention and increase hydrological connectivity between fields and streams, thereby accelerating pesticide and nutrient delivery to surface waters. Vegetation and riparian buffers act as filters by trapping sediments, adsorbed pesticides, and particulate phosphorus; loss of this cover increases both dissolved and sediment-bound transport. Evidence from Uganda indicates higher storm runoff volumes and higher nitrogen losses from degraded plots compared with forested plots [48,58]. Similarly, Obubu et al. [48] reported higher nitrate and phosphorus concentrations in deforested sub-catchments relative to forested basins. In several reviewed basins, studies also describe degradation of riparian buffer zones, which plausibly reduces interception capacity and increases contaminant delivery during stormflow [71].

4.2.3. Climatic Factors and Rainfall Variability

Climate factors compound agrochemical runoff risk because heavy rainfall events mobilize contaminants rapidly through surface runoff and erosion, producing short-duration concentration pulses in receiving waters. Studies in the region report higher pesticide and nutrient concentrations during rainy periods and shortly after storms [49]. Beyond Eastern Africa, evidence from monitored agricultural watersheds shows that extreme precipitation is associated with disproportionate increases in discharge and nutrient loads, including phosphorus, illustrating how storm hydrology can dominate annual export [72,73]. While the magnitude of these responses is watershed-specific, the mechanism, event-driven mobilization, supports interpreting seasonal spikes in Eastern African basins as runoff-linked pulses rather than steady-state contamination. These patterns are consistent with climate assessments indicating that heavy precipitation and hydrological extremes are projected to intensify in parts of East Africa, which could increase the frequency of runoff-driven contamination episodes unless countered by catchment-scale management (IPCC AR6) [74,75].

4.3. Ecological and Human Health Impacts of Agrochemical Runoff

The reviewed evidence indicates that pesticide and nutrient inputs to surface waters are associated with multiple ecological stressors and human exposure pathways, although the strength of attribution to agriculture varies by basin depending on co-occurring sources (e.g., urban wastewater). In large basins such as Lake Victoria and Lake Naivasha, multiple pollution sources including commercial agriculture, untreated urban wastewater, and industrial effluent co-occur. Our synthesis therefore distinguishes between plot-scale evidence, where attribution to smallholder farming is clear, and basin-scale evidence, where attribution remains shared and uncertain. Although several basins such as Lake Victoria and Lake Naivasha were investigated repeatedly, our use of ranges rather than pooled averages reduces pseudo-replication. Nonetheless, geographic bias toward Kenya and Tanzania remains a limitation of the evidence base. Because "conventional" farming encompassed diverse practices across sites, from moderate-input smallholder maize to high-input irrigated horticulture, these ranges are interpreted as descriptive contrasts across independent studies rather than uniform categories. Elevated phosphorus and nitrogen concentrations were frequently reported alongside eutrophication indicators, including harmful algal blooms and dissolved oxygen depletion in several lake systems [2,49]. In studies that reported dissolved oxygen during bloom events, DO occasionally fell below commonly used hypoxia thresholds (e.g., ~4 mg L^{-1}), conditions that can contribute to fish stress and localized mortality. Although strong correlations between phosphorus and chlorophyll-a were observed, bloom dynamics in the East African Great Lakes are also influenced by hydro-meteorological factors such as water level fluctuations and thermal stratification. Moreover, fishery decline reflects the combined effects of eutrophication, overfishing, and invasive species introductions (e.g., Nile Perch), highlighting that ecological degradation arises from multiple interacting stressors rather than agrochemical inputs alone. Cyanobacteria blooms were also reported to coincide with microcystin occurrence in several sites. Reported microcystin concentrations ranged between 2.5 and 5.8 μg L^{-1}, and exceeded the WHO provisional guideline value for microcystins in drinking water (1 μg L^{-1}; lifetime, based on MC-LR) [44,52].

Fish sampled from contaminated rivers and lakes contained organochlorine residues such as DDT and aldrin at concentrations ranging from 0.12 to 0.35 μg kg^{-1} in fish muscle, exceeding the food-safety reference limits applied in the respective studies [38,44]. These studies compared detected residues with Codex-based maximum residue limits for organochlorine pesticides in fish products, suggesting potential dietary exposure risks for communities relying on these fisheries. In the Nyando catchment, studies reported reduced fish diversity metrics concurrent with pesticide detections and other environmental pressures; however, the extent to which pesticide exposure alone explains observed biodiversity changes remains context-specific [42].

Human health may arise through multiple pathways, including drinking-water intake (where surface water is used untreated or partially treated), dietary exposure (e.g., fish consumption), and occupational exposure during pesticide handling. For nitrate, interpretation depends on how concentrations are reported (as nitrate vs. nitrate-N): WHO's drinking-water guideline is 50 mg L^{-1} as nitrate (≈11 mg L^{-1} as nitrate-N), set to protect bottle-fed infants from methemoglobinemia [2,76,77]. Accordingly, reported concentrations should be evaluated against the appropriate unit basis before concluding exceedance. For pesticides, the epidemiological literature has linked chronic exposure to certain compounds with neurological and endocrine outcomes, but linking observed environmental concentrations in specific basins to population-level disease burdens requires careful exposure assessment and is seldom available in the included studies [46,71]. The evidence base supports concern about potential ecological impairment and human exposure, but also highlights limitations in long-term monitoring, mixture assessment, and attribution to smallholder agriculture versus other sources.

4.4. Policy Gaps and Regulatory Challenges

Growing evidence of agrochemical contamination in surface waters across Eastern Africa highlights persistent weaknesses in regulatory implementation and monitoring capacity. Although national pesticide regulatory authorities and environmental management agencies exist in many countries, enforcement capacity and monitoring coverage remain limited, and coordination between agricultural extension services and water-resource management institutions is often weak. The reviewed studies indicate that these institutional gaps translate into uneven compliance and limited risk reduction at farm level. For example, several studies reported detections of legacy pesticides (including DDT-related compounds) in surface waters and biota, which may reflect historical use and/or continuing inputs; distinguishing between these requires targeted enforcement data and source-tracing that are rarely reported [44,78]. Where compliance surveys were available, they suggested limited adherence to recommended handling, storage, and disposal practices, implying that regulatory standards do not consistently translate into on-farm risk reduction [42,46].

A recurring barrier is constrained farmer support systems. Across multiple studies, access to extension services and/or formal credit was limited, restricting the adoption of integrated pest management (IPM), calibrated application, soil conservation, and nutrient stewardship practices [57,64,65]. Rather than repeating country-specific percentages, the synthesis of the reported values indicates a consistent pattern: low advisory coverage and input-cost constraints tend to favour blanket application practices and reduce uptake of runoff-mitigation measures.

Monitoring and risk assessment frameworks also show major gaps. Routine water-quality programs often focus on a limited set of analytes and single-compound reporting, while the evidence base increasingly indicates that mixtures (pesticides + nutrients) can contribute to cumulative ecological risk. This creates a mismatch between regulatory needs and available surveillance capacity. Developing harmonized monitoring indicators, improving laboratory capacity, and adopting mixture-aware assessment approaches are therefore policy priorities for basin authorities and national regulators. In addition, several countries lack harmonized monitoring frameworks capable of detecting pesticide mixtures and cumulative ecological risks. This contrasts with OECD monitoring approaches that emphasize standardized indicators, long-term datasets, and coordinated reporting systems for agricultural pollution [79]. Most monitoring programs evaluate individual contaminants separately, yet aquatic ecosystems are typically exposed to mixtures of pesticides and nutrients whose combined ecological effects may differ from single-compound toxicity thresholds [60,69].

This review is not without limitations. The synthesis relied primarily on peer-reviewed journal articles, which may introduce publication bias because studies reporting significant contamination results are more likely to be published than studies reporting null findings. Consequently, the patterns identified in this review should be interpreted as representative of the available scientific literature rather than a complete inventory of monitoring results across the region, as relevant gray literature or unpublished national monitoring records may not have been captured. In addition, considerable heterogeneity across studies in sampling design, analytical methods, analyte coverage, and monitoring duration limits direct comparison of reported concentrations. Spatial gaps persist in some countries (e.g., Somalia and Eritrea), and differences in detection limits add further uncertainty. Accordingly, this review reports ranges and study-level values rather than pooled averages, to avoid misleading impressions of precision. These limitations reinforce the need for standardized long-term monitoring and improved reporting quality across the region.

4.5. Future Research Directions

Future research should address several limitations identified in the current literature. First, long-term monitoring programs are needed to better characterize seasonal and interannual variability in pesticide and nutrient contamination across Eastern African catchments. Second, most existing studies assess individual compounds rather than combined exposures, highlighting the need for mixture-toxicity studies that examine cumulative ecological risks associated with multiple pesticides and nutrients occurring simultaneously in aquatic environments. Third, EQS/PNEC values were not consistently available for all compounds, reflecting gaps in ecotoxicological data for Eastern Africa and limiting the scope of ecological risk comparisons. Expanding toxicity datasets and establishing regionally relevant thresholds would strengthen future ecological risk assessments. Fourth, more research is needed to better distinguish contributions from smallholder agriculture relative to other pollution sources such as urban wastewater and industrial discharges in mixed-use basins. Fifth, future monitoring should explicitly include emerging pesticide classes such as neonicotinoids and systemic fungicides. Their omission from most existing datasets reflects both limited adoption by smallholder farmers and analytical challenges in regional laboratories. Addressing these gaps will be critical to ensure that ecological risk assessments remain comprehensive and up to date. Finally, interdisciplinary studies integrating hydrology, agronomy, socio-economics, and policy analysis would help identify practical strategies for reducing agrochemical runoff while maintaining agricultural productivity. Future reviews may also consider additional pollutants, such as heavy metals beyond pesticides and nutrients, to broaden the evidence base.

5. Conclusions

This systematic review synthesizes evidence indicating that pesticide and nutrient contamination of surface waters is widely reported across Eastern Africa, with patterns frequently linked to agricultural intensification and rainfall-driven runoff processes. The consistency of observations across multiple catchments suggests that these contamination patterns reflect broader land-use pressures rather than isolated local events. Ecological responses, including eutrophication and changes in aquatic biodiversity indicators, were reported in several studies, while evidence of mitigation measures demonstrates that reductions of 50–80% in agrochemical runoff are achievable under appropriate management practices. However, progress remains constrained by limited long-term monitoring datasets, fragmented regulatory implementation, and restricted farmer access to advisory services and financial support for sustainable practices. Addressing these challenges will require stronger coordination between agricultural and water-resource governance systems, expansion of harmonized water-quality monitoring networks, and increased support for farmers to adopt runoff-mitigation practices such as buffer strips, conservation tillage, and integrated nutrient management. Future research should prioritize improved assessment of pesticide mixtures and cumulative ecological risks, alongside deeper analysis of socio-economic factors influencing adoption of sustainable farming practices, in order to support evidence-based water-quality management under ongoing agricultural expansion and climate variability. Interpretation of basin-scale findings should be made cautiously, as multiple pollution sources co-occur alongside smallholder farming. Future systematic reviews can also adopt watershed-level synthesis and improve geographic balance to further reduce pseudo-replication and ensure more representative regional conclusions.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/pollutants6020032/s1, Supplementary Figure S1. The number of reviewed literature based on the year of publication; Supplementary Figure S2. Geographic distribution of included studies across Eastern Africa by water bodies/catchments; Supplementary Table S1. PRISMA 2020 Checklist; Supplementary Table S2. Inclusion an Exclusion Criteria; Supplementary Table S3. Data extraction categories and variables; Supplementary Table S4. Summary Characteristics of the 35 included studies; Supplementary Table S5. Evidence of pesticide occurrence in Eastern African surface waters (2010–2024); Supplementary Table S6. Statistical associations between pesticide application intensity and indicators of aquatic ecosystem degradation; Supplementary Table S7. Agricultural practices and loss of nutrients and pesticides; Supplementary Table S8. Crop production and runoff into water sources; Supplementary Table S9. Conservation vs. minimum tillage; Supplementary Table S10. Seasonal differences in pesticide and nutrient runoff; Supplementary Table S11. Adoption of best management practices (BMPs) by farmer education level Sources; Supplementary Table S12. Cost and savings comparison of conventional vs. sustainable systems; Supplementary Table S13. Temporal trends in pesticides concentrations in Nyando River; Supplementary Table S14. Long-term nutrient and eutrophication trends in Lake Victoria.

Author Contributions: Conceptualization, D.M.O., S.M.M. and C.M.; methodology, D.M.O., S.M.M., C.M., N.K. and R.N.O.; formal analysis, D.M.O.; investigation, D.M.O., S.M.M., N.K. and R.N.O.; resources, F.B. and C.M.; data curation, D.M.O.; writing—original draft preparation, D.M.O.; writing—review and editing, S.M.M., N.K., R.N.O., C.M. and F.B.; visualization, D.M.O.; supervision, S.M.M., N.K., C.M. and R.N.O.; project administration, S.M.M.; funding acquisition, F.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: No new primary data were generated. The data supporting the findings of this study are extracted from published articles cited in the manuscript and are available within the article and its Supplementary Materials.

Acknowledgments: I gratefully acknowledge the International Institute of Tropical Agriculture (IITA), under the CGIAR Agroecology Initiative, for providing scholarship support that covered my tuition fees during the period in which this review was conducted. I also appreciate the stipend support provided by the International Livestock Research Institute (ILRI), which sustained me during the study. The findings and opinions presented in this paper are solely those of the authors and do not necessarily reflect the official views of IITA, ILRI, or CGIAR.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of this study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Abbreviations

The following abbreviations are used in this manuscript:

ASALs	Arid and Semi-Arid Lands
CPUE	Catch per Unit Effort
DDT	Dichlorodiphenyltrichloroethane
EQS	Environmental Quality Standard
DO	Dissolved Oxygen
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
HABs	Harmful Algal Blooms
IPCC AR6	Intergovernmental Panel on Climate Change Sixth Assessment Report
IPM	Integrated Pest Management
MC-LR	Microcystin-LR (leucine–arginine variant of microcystin toxin)
MRL	Maximum Residue Limit
OECD	Organisation for Economic Co-operation and Development
PNEC	Predicted No-Effect Concentration
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
USD	United States Dollar
WHO	World Health Organization

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