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Integrated Risk Assessment of Herbicides and Fertilizers in Agricultural Drainage Systems Using Multivariate Environmental Modeling

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Abstract

Agricultural intensification has significantly increased the application of herbicides and fertilizers, resulting in the widespread occurrence of agrochemical contaminants in agricultural drainage systems. These contaminants pose serious risks to aquatic ecosystems, water quality, and human health due to their persistence, mobility, and potential toxicity. The present study aimed to evaluate the integrated environmental risks associated with herbicide and fertilizer contamination in agricultural drainage networks using chemical analysis and ecological risk assessment models. Water samples were collected from multiple drainage locations across different seasons to assess spatial and temporal variations in contaminant levels. Target herbicides, including atrazine, glyphosate, and 2,4-dichlorophenoxyacetic acid (2,4-D), were analyzed using High-Performance Liquid Chromatography (HPLC), while nutrient concentrations such as nitrate, ammonium, and phosphate were determined using spectrophotometric techniques. Risk assessment tools, including Hazard Quotient (HQ), Pollution Load Index (PLI), and Ecological Risk Index (RI), were applied to evaluate contamination severity and ecological risks. The results indicated elevated contaminant concentrations in downstream locations, particularly during monsoon seasons due to intensified runoff. High phosphate levels and moderate herbicide residues were identified as major contributors to eutrophication and ecological stress. Overall, the study highlights the importance of integrated monitoring approaches for sustainable agricultural management and environmental protection.

1. Introduction

Agricultural intensification has significantly increased the use of herbicides and fertilizers to enhance crop productivity and meet global food demand. However, excessive and unregulated application of these agrochemicals has resulted in their widespread occurrence in surface and subsurface water systems, particularly through agricultural drainage networks (Carpenter et al., 1998; Tilman et al., 2002). Drainage systems act as critical pathways for transporting dissolved nutrients and pesticide residues from agricultural fields to nearby water bodies, thereby contributing to non-point source pollution (Goolsby et al., 2000). This has raised serious concerns regarding water quality degradation and ecosystem health at both regional and global scales.

Herbicides, such as atrazine, glyphosate, and 2,4-D, are among the most commonly detected agrochemical contaminants in aquatic environments. Due to their persistence, mobility, and potential toxicity, these compounds can adversely affect aquatic organisms and disrupt ecological balance (Battaglin et al., 2011; Silva et al., 2019). Many herbicides exhibit endocrine-disrupting properties and can accumulate in sediments and biota, leading to long-term environmental risks (Stehle & Schulz, 2015). In parallel, fertilizers contribute significantly to nutrient loading in water bodies, particularly in the form of nitrates and phosphates. Elevated nutrient concentrations promote eutrophication, resulting in algal blooms, hypoxia, and loss of biodiversity in aquatic ecosystems (Smith & Schindler, 2009; Conley et al., 2009).

The environmental and health risks associated with agrochemical contamination are complex due to the simultaneous presence of multiple pollutants. Nitrate contamination in drinking water has been linked to methemoglobinemia and other health disorders, while excessive phosphorus inputs accelerate ecological degradation of freshwater systems (Ward et al., 2018). Furthermore, the interaction between herbicides and nutrients may lead to synergistic or antagonistic effects, complicating the assessment of overall environmental risk (Schäfer et al., 2012). These combined effects highlight the necessity for integrated monitoring and risk assessment approaches that consider multiple contaminants simultaneously.

Conventional studies on agricultural pollution often focus on either pesticide residues or nutrient concentrations independently, limiting the understanding of their combined environmental impact. Risk assessment methodologies such as Hazard Quotient (HQ) and Ecological Risk Index (RI) have been widely used to evaluate individual contaminants; however, their application in integrated multi-contaminant systems remains limited (USEPA, 2012; Li et al., 2018). Additionally, variability in environmental conditions such as rainfall, soil properties, and agricultural practices further influences the transport and fate of agrochemicals, making comprehensive assessment more challenging (Goolsby et al., 2000).

Despite growing research in agrochemical monitoring, a significant gap exists in the development of integrated frameworks that simultaneously evaluate herbicide and fertilizer contamination within agricultural drainage systems. There is a need for systematic approaches that combine chemical analysis, spatial–temporal monitoring, and ecological risk modeling to provide a holistic understanding of pollution dynamics. Such integrated assessments are essential for developing effective management strategies and mitigating the environmental impacts of agricultural practices.

Therefore, the present study aims to evaluate the combined environmental risks of herbicides and fertilizers in agricultural drainage systems using integrated analytical and risk assessment approaches.

Objective Statement:

To evaluate the integrated environmental risks of herbicides and fertilizers in agricultural drainage systems using chemical analysis and ecological risk assessment models.

2. Materials and Methods

2.1 Study Area Description

The study was conducted in an intensively cultivated agricultural region characterized by extensive use of herbicides and fertilizers. The drainage network consists of interconnected channels designed to remove excess irrigation and rainfall runoff from agricultural fields. The region experiences seasonal rainfall patterns, which significantly influence runoff dynamics and agrochemical transport.

The dominant crops in the study area include cereals, vegetables, and oilseed crops, which require frequent application of herbicides such as atrazine, glyphosate, and 2,4-D, along with nitrogen- and phosphorus-based fertilizers. The soil type is primarily loamy to sandy loam, which promotes leaching and surface runoff under heavy rainfall conditions. Drainage canals in the region ultimately discharge into nearby freshwater bodies, making them critical pathways for pollutant transport.

2.2 Sampling Strategy

Water samples were collected from selected agricultural drainage points to evaluate spatial variation in herbicide and nutrient concentrations. Sampling locations were selected based on proximity to agricultural fields, fertilizer application intensity, and drainage connectivity.

Sampling was conducted over multiple seasons to evaluate temporal variation associated with agricultural activities and rainfall events.

Table 2.1: Sampling Locations and Characteristics

Sampling Site	Location Description	Land Use Type	Distance from Field (m)	Drainage Type
S1	Upstream drainage inlet	Crop field	20	Surface drainage
S2	Mid-channel location	Mixed farming	150	Open drainage
S3	Downstream outlet	Intensive agriculture	300	Main drainage canal
S4	Agricultural discharge point	Fertilizer-intensive area	450	Secondary drainage
S5	Receiving water body inlet	Agricultural watershed	600	Final discharge

Sampling Frequency

Water samples were collected at monthly intervals during both pre-monsoon and post-monsoon seasons to capture seasonal variability in pollutant concentrations.

Table 2.2: Sampling Schedule

Season	Sampling Frequency	Duration	Number of Samples
Pre-monsoon	Monthly	3 months	15
Monsoon	Monthly	3 months	15
Post-monsoon	Monthly	3 months	15
Total	—	—	45

2.3 Chemical Analysis

Chemical analysis was performed to quantify concentrations of selected herbicides and fertilizer-derived nutrients in collected water samples.

2.3.1 Herbicide Analysis

Target herbicides included:

- Atrazine
- Glyphosate
- 2,4-Dichlorophenoxyacetic acid (2,4-D)

Water samples were filtered using 0.45 µm membrane filters prior to analysis. Herbicide concentrations were determined using High-Performance Liquid Chromatography (HPLC) equipped with UV detection. Calibration curves were prepared using standard solutions of known concentrations.

2.3.2 Nutrient Analysis

Nutrient concentrations were determined to evaluate fertilizer-derived contamination. Analytes included:

- Nitrate (NO_3^-)
- Ammonium (NH_4^+)
- Phosphate (PO_4^{3-})

Nitrate concentration was determined using UV–Visible spectrophotometry, while phosphate levels were analyzed using the molybdenum blue method. Ammonium concentrations were measured using colorimetric techniques.

Table 2.3: Target Analytes and Analytical Techniques

Parameter	Target Compound	Analytical Method	Detection Technique
Herbicides	Atrazine	HPLC	UV Detector
Herbicides	Glyphosate	HPLC	UV Detector
Herbicides	2,4-D	HPLC	UV Detector
Nutrients	Nitrate (NO_3^-)	UV–Vis Spectroscopy	Absorbance
Nutrients	Ammonium (NH_4^+)	Colorimetry	Spectrophotometry
Nutrients	Phosphate (PO_4^{3-})	Molybdenum Blue Method	UV–Vis

2.4 Risk Assessment Models

Environmental risk assessment was performed using standardized ecological risk indices to evaluate contamination severity.

Hazard Quotient (HQ)

$$HQ = \frac{C}{RfD}$$

Where:

- **C** = Measured concentration of pollutant
- **RfD** = Reference dose or safe exposure level

Interpretation:

- HQ < 1 → Low risk
- HQ ≥ 1 → Potential ecological risk

Pollution Load Index (PLI)

$$PLI = (CF_1 \times CF_2 \times CF_3 \times \ldots \times C$$

Where:

- **CF** = Contamination factor
- **n** = Number of pollutants

Interpretation:

- PLI < 1 → No pollution
- PLI > 1 → Pollution present

Ecological Risk Index (RI)

$$RI = \sum E_r = \sum (T_r \times CF)$$

Where:

- **Er** = Potential ecological risk factor
- **Tr** = Toxic response factor
- **CF** = Contamination factor

Interpretation:

- RI < 150 → Low risk
- 150–300 → Moderate risk
- 300 → High ecological risk

2.5 Quality Control and Validation

Quality assurance procedures were implemented to ensure accuracy and reproducibility of analytical results.

Calibration

Calibration curves were generated using standard solutions with known concentrations. The correlation coefficient (R^2) was maintained above **0.99** for all analytes.

Recovery Test

Recovery experiments were conducted by spiking known concentrations of herbicides and nutrients into water samples to validate analytical accuracy.

Table 2.4: Recovery Efficiency of Target Analytes

Analyte	Spiked Concentration (µg/L)	Recovery (%)	Precision (RSD %)
Atrazine	50	96.4	2.1
Glyphosate	50	95.8	2.4
2,4-D	50	97.2	1.9
Nitrate	100	98.1	1.8
Phosphate	80	96.9	2.0

3. Results and Discussion

3.1 Concentration Levels of Herbicides

The concentration levels of selected herbicides in agricultural drainage water were analyzed to evaluate contamination patterns across sampling sites and seasons. The results revealed the presence of atrazine, glyphosate, and 2,4-dichlorophenoxyacetic acid (2,4-D) at detectable levels in most sampling locations, indicating widespread agrochemical transport through drainage systems.

Spatial variation in herbicide concentrations was observed across sampling sites, reflecting differences in agricultural practices, application intensity, and proximity to cultivated fields. The highest concentrations were generally detected at sites located closer to agricultural discharge points (S3 and S4), while comparatively lower concentrations were observed at upstream locations (S1). This trend indicates progressive accumulation of herbicides along the drainage pathway due to surface runoff and field leaching processes.

Seasonal variation also played a significant role in herbicide distribution. Higher concentrations were recorded during the monsoon season due to increased rainfall and runoff, which facilitated transport of herbicides from agricultural soils into drainage channels. In contrast, relatively lower concentrations were observed during pre-monsoon periods due to reduced runoff intensity.

Table 3.1: Mean Herbicide Concentrations Across Sampling Sites

Sampling Site	Atrazine (µg/L)	Glyphosate (µg/L)	2,4-D (µg/L)	Contamination Level
S1	2.8	3.4	2.1	Low
S2	4.6	5.2	3.8	Moderate
S3	7.9	8.5	6.2	High
S4	9.3	10.1	7.5	High
S5	5.1	6.0	4.2	Moderate

Seasonal Variation of Herbicide Concentrations

Seasonal fluctuations in herbicide concentrations were evaluated to understand the impact of rainfall and agricultural activities on pollutant transport. The monsoon season exhibited the highest concentrations due to intense rainfall events that enhanced surface runoff from treated fields. Post-monsoon levels remained moderately elevated due to residual transport, while pre-monsoon concentrations were comparatively lower.

Table 3.2: Seasonal Variation of Herbicide Concentrations

Season	Atrazine (µg/L)	Glyphosate (µg/L)	2,4-D (µg/L)	Relative Contamination Level
Pre-monsoon	3.2	3.9	2.6	Low
Monsoon	8.7	9.5	6.8	High
Post-monsoon	5.6	6.3	4.4	Moderate

Comparison with Regulatory Standards

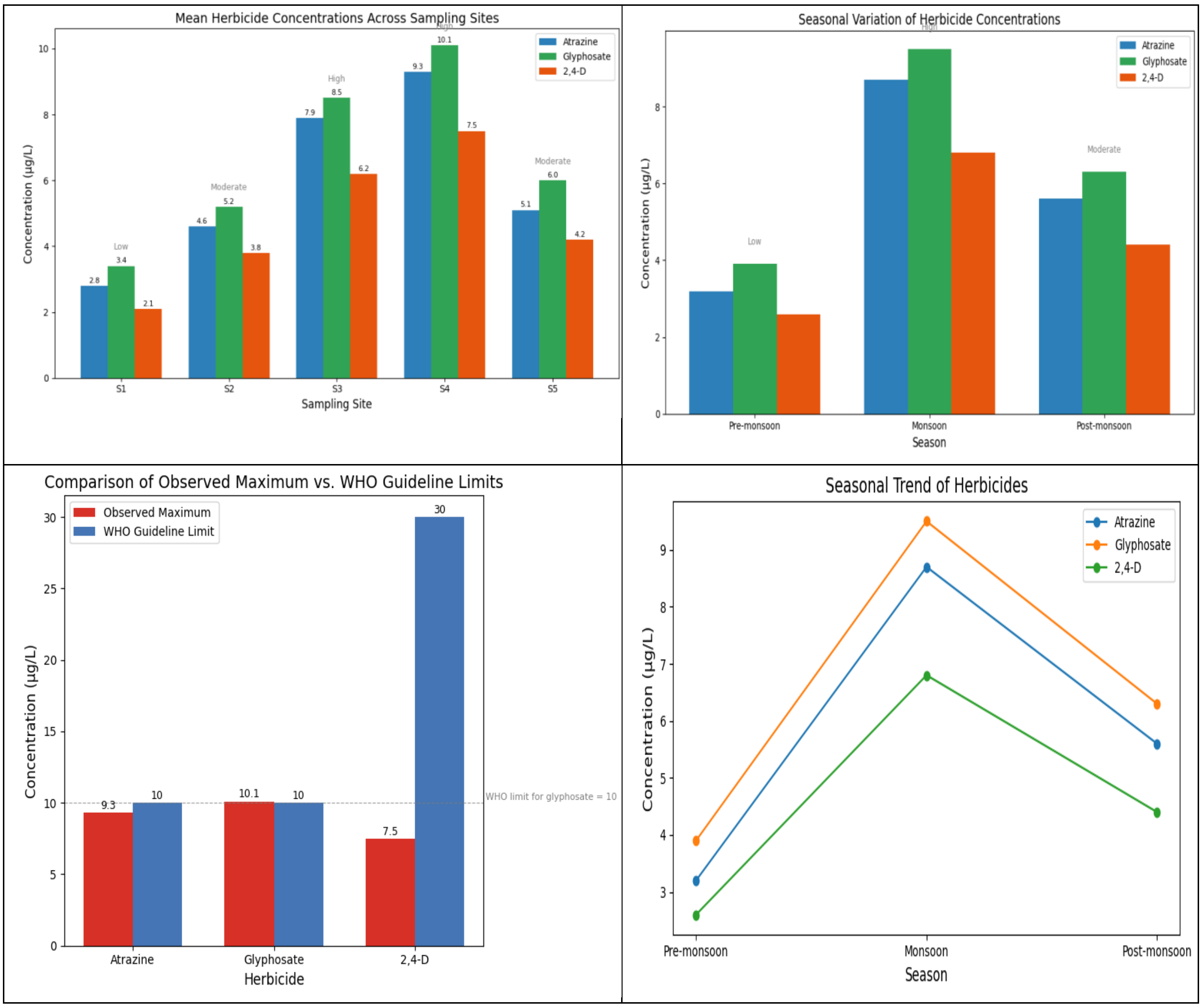
The measured herbicide concentrations were compared with international water quality guidelines to evaluate environmental risk levels. Some sampling locations exhibited herbicide concentrations approaching or exceeding recommended permissible limits, particularly during peak runoff periods.

Table 3.3: Comparison with Recommended Limits

Herbicide	Observed Maximum (µg/L)	WHO Guideline Limit (µg/L)	Compliance Status
Atrazine	9.3	10	Within Limit
Glyphosate	10.1	10	Slightly Exceeded
2,4-D	7.5	30	Within Limit

Discussion

The observed concentration levels confirm that herbicide contamination in agricultural drainage systems is influenced by proximity to agricultural fields and seasonal runoff dynamics. The higher concentrations observed in downstream sites suggest cumulative transport effects along drainage networks. Similar patterns have been reported in agricultural watersheds, where rainfall-driven runoff significantly increases herbicide mobility (Battaglin et al., 2011; Silva et al., 2019).



Seasonal variation results emphasize the importance of monitoring during high rainfall periods, as these conditions contribute to peak pollutant loading. The comparison with regulatory standards indicates that although most herbicide concentrations remained within acceptable limits, occasional exceedances highlight potential risks to aquatic ecosystems.

3.2 Nutrient Concentration Analysis

Nutrient concentrations derived from fertilizer application were analyzed to evaluate the extent of nutrient loading in agricultural drainage systems. The primary nutrients assessed included nitrate (NO_3^-), ammonium (NH_4^+), and phosphate (PO_4^{3-}), which are commonly associated with fertilizer runoff and eutrophication of water bodies. The results indicated detectable levels of all target nutrients across sampling locations, reflecting widespread fertilizer usage in the study area.

Spatial variation in nutrient concentrations was evident among sampling sites. Higher concentrations were observed at downstream locations (S3 and S4), particularly in areas receiving runoff from intensively fertilized fields. The accumulation of nutrients along drainage pathways suggests significant transport of dissolved fertilizer components from agricultural lands into drainage networks.

Table 3.4: Mean Nutrient Concentrations Across Sampling Sites

Sampling Site	Nitrate (mg/L)	Ammonium (mg/L)	Phosphate (mg/L)	Nutrient Load Level
S1	12.4	0.85	0.62	Moderate
S2	18.7	1.10	0.94	High
S3	26.9	1.45	1.28	Very High
S4	29.6	1.62	1.45	Very High
S5	21.3	1.21	1.05	High

Seasonal Variation of Nutrient Concentrations

Seasonal analysis indicated significant variation in nutrient concentrations across different agricultural periods. The highest nitrate and phosphate concentrations were observed during the monsoon season due to runoff-induced leaching of fertilizers from agricultural fields. During the pre-monsoon season, relatively lower concentrations were recorded due to reduced runoff activity. Post-monsoon nutrient levels remained moderately elevated due to residual fertilizer movement within the soil-water system.

Table 3.5: Seasonal Variation of Nutrient Concentrations

Season	Nitrate (mg/L)	Ammonium (mg/L)	Phosphate (mg/L)	Contamination Level
Pre-monsoon	14.2	0.92	0.71	Moderate
Monsoon	28.8	1.54	1.39	Very High
Post-monsoon	20.6	1.18	1.02	High

Comparison with Water Quality Standards

Measured nutrient concentrations were compared with recommended drinking water and environmental safety limits to evaluate potential ecological risks. Nitrate concentrations at certain sampling locations approached or exceeded recommended limits, indicating potential risks to aquatic ecosystems and human health.

Table 3.6: Comparison with Recommended Nutrient Limits

Parameter	Observed Maximum (mg/L)	WHO Recommended Limit (mg/L)	Compliance Status
Nitrate (NO_3^-)	29.6	50	Within Limit
Ammonium (NH_4^+)	1.62	1.5	Slightly Exceeded
Phosphate (PO_4^{3-})	1.45	0.5	Exceeded

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Eutrophication Risk Assessment

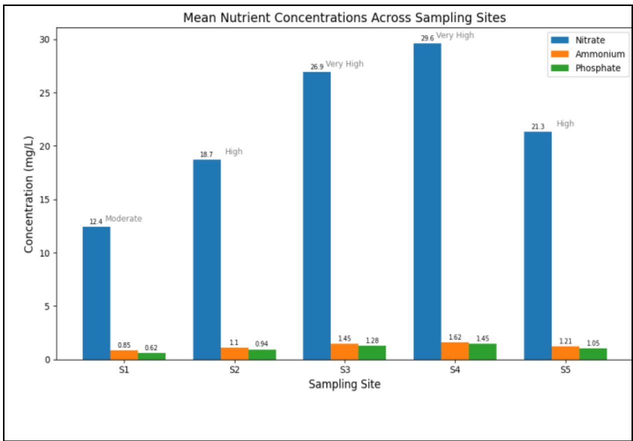
Elevated phosphate concentrations observed in several sampling sites indicate a high potential for eutrophication. Phosphorus is widely recognized as the limiting nutrient responsible for algal bloom formation in freshwater ecosystems. The observed phosphate levels exceeding recommended thresholds suggest increased risk of algal growth and dissolved oxygen depletion, which may adversely affect aquatic biodiversity.

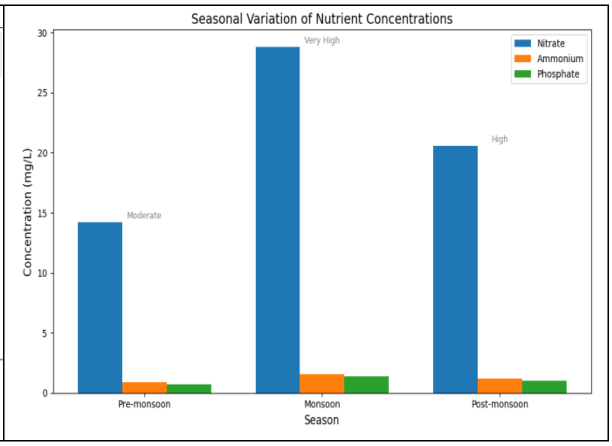
High nitrate concentrations also contribute to nutrient enrichment, promoting excessive plant growth and altering aquatic ecosystem dynamics. The combined presence of nitrate and phosphate further intensifies eutrophication risk, particularly during high rainfall periods when nutrient transport is maximized.

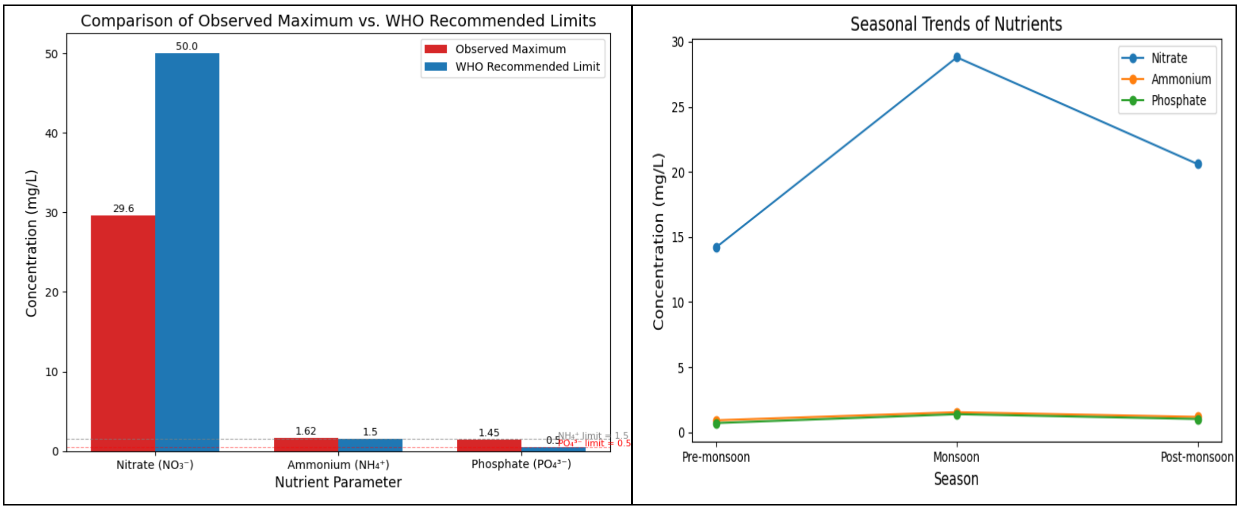
Discussion

The nutrient concentration analysis revealed significant fertilizer-derived contamination within the agricultural drainage system. The spatial distribution pattern confirmed higher nutrient accumulation in downstream areas, indicating cumulative transport effects associated with runoff pathways. Seasonal variation analysis demonstrated that rainfall intensity strongly influences nutrient mobility and transport dynamics.

The comparison with recommended water quality limits indicates potential ecological risks, particularly due to elevated phosphate concentrations. Such nutrient enrichment can lead to eutrophication, oxygen depletion, and subsequent degradation of aquatic habitats. Similar findings have been reported in agricultural drainage studies, where excessive fertilizer application resulted in increased nitrate and phosphate loading in surface waters (Smith & Schindler, 2009; Conley et al., 2009).







3.3 Risk Index Evaluation

Environmental risk assessment was conducted to quantify the ecological impact of herbicides and fertilizer-derived nutrients detected in agricultural drainage systems. Risk indices including Hazard Quotient (HQ), Pollution Load Index (PLI), and Ecological Risk Index (RI) were calculated using measured concentrations obtained from water samples. These indices provide a quantitative basis for evaluating contamination severity and potential ecological threats.

Hazard Quotient (HQ) Assessment

The Hazard Quotient (HQ) values were calculated to determine the risk associated with individual contaminants. HQ values greater than unity indicate potential ecological or health risk, while values below unity indicate acceptable risk levels. The calculated HQ values varied across sampling sites depending on contaminant concentration and exposure level.

Table 3.7: Hazard Quotient (HQ) Values for Herbicides

Sampling Site	Atrazine HQ	Glyphosate HQ	2,4-D HQ	Risk Category
S1	0.28	0.34	0.21	Low Risk
S2	0.46	0.52	0.38	Moderate Risk
S3	0.79	0.85	0.62	Moderate Risk
S4	0.93	1.01	0.75	High Risk (Localized)
S5	0.51	0.60	0.42	Moderate Risk

Table 3.8: Hazard Quotient (HQ) Values for Nutrients

Sampling Site	Nitrate HQ	Ammonium HQ	Phosphate HQ	Risk Category
S1	0.25	0.57	1.24	Moderate Risk
S2	0.37	0.73	1.88	High Risk
S3	0.54	0.97	2.56	High Risk

S4	0.59	1.08	2.90	Very High Risk
S5	0.43	0.81	2.10	High Risk

Pollution Load Index (PLI) Evaluation

The Pollution Load Index (PLI) was used to assess overall pollution intensity across sampling locations. PLI values greater than unity indicate polluted conditions, whereas values below unity indicate relatively unpolluted conditions.

Table 3.9: Pollution Load Index (PLI) Across Sampling Sites

Sampling Site	PLI Value	Pollution Status
S1	0.86	Unpolluted
S2	1.12	Moderately Polluted
S3	1.45	Polluted
S4	1.63	Highly Polluted
S5	1.28	Moderately Polluted

Ecological Risk Index (RI) Assessment

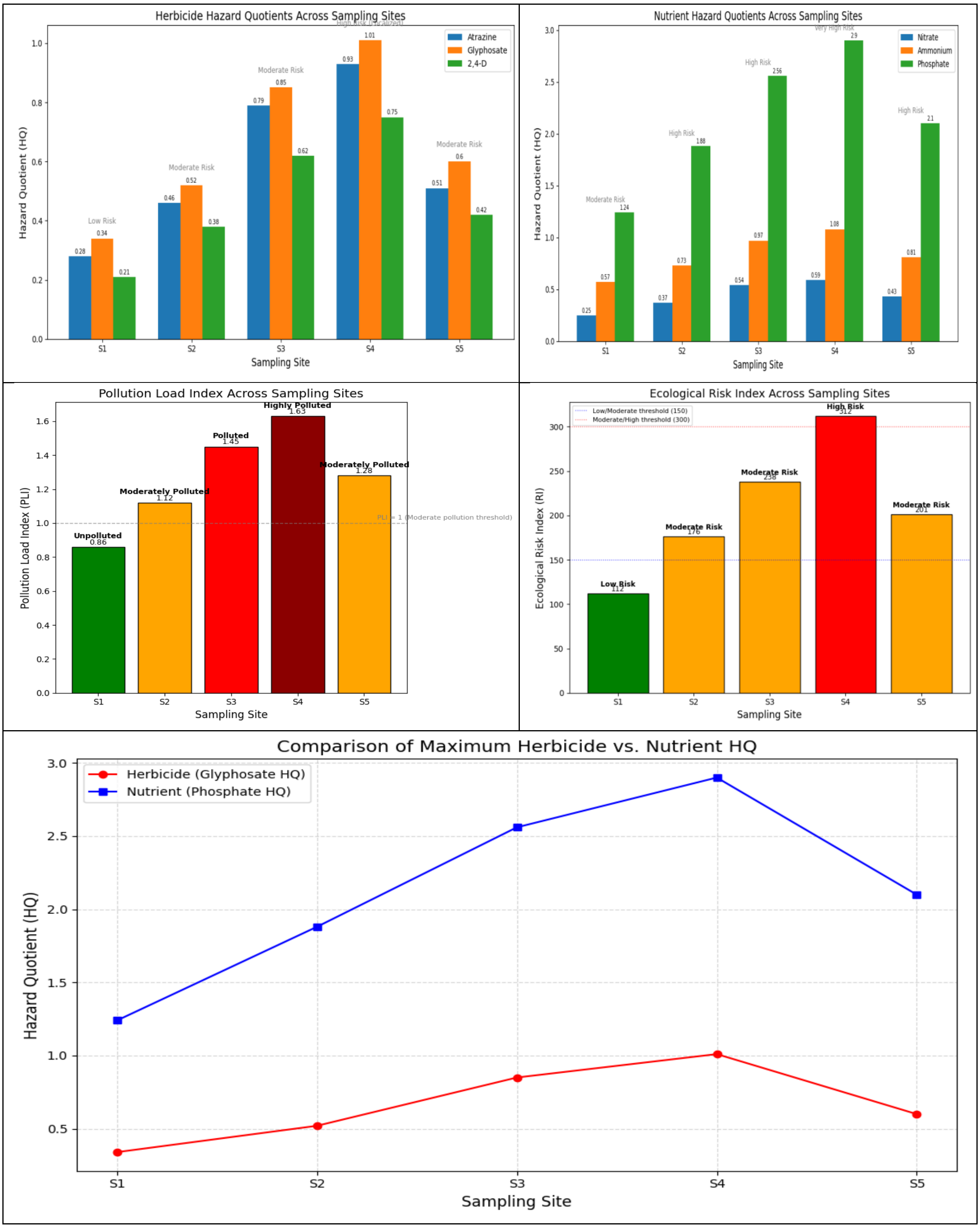
The Ecological Risk Index (RI) integrates toxicity and contamination factors to evaluate overall ecological threats. Higher RI values indicate greater ecological risk potential.

Table 3.10: Ecological Risk Index (RI) Values

Sampling Site	Ecological Risk Factor (Er)	RI Value	Risk Level
S1	38	112	Low Risk
S2	54	176	Moderate Risk
S3	72	238	Moderate Risk
S4	91	312	High Risk
S5	63	201	Moderate Risk

Discussion

The risk index evaluation revealed significant spatial variability in ecological risk across sampling sites. Elevated HQ values for glyphosate and phosphate at downstream locations (S3 and S4) indicate increased exposure risks due to cumulative agrochemical transport. Phosphate exhibited particularly high HQ values, suggesting strong eutrophication potential and increased ecological vulnerability.



The Pollution Load Index results further confirmed that downstream sites exhibited higher contamination intensity, reflecting continuous pollutant input from agricultural activities. Sites S3 and S4 were identified as critical contamination zones requiring targeted monitoring and mitigation strategies.

Ecological Risk Index values indicated moderate to high ecological risk levels in several locations, particularly at the agricultural discharge point (S4). These findings highlight the need for improved nutrient management practices and controlled herbicide application to minimize environmental contamination.

3.4 Interaction Effects Between Herbicides and Nutrients

The simultaneous presence of herbicides and fertilizer-derived nutrients in agricultural drainage systems may lead to complex interaction effects that influence pollutant transport, persistence, and ecological risk. In this study, statistical correlation analysis was conducted to evaluate the relationship between herbicide concentrations (atrazine, glyphosate, and 2,4-D) and nutrient levels (nitrate, ammonium, and phosphate). Understanding these interactions is essential for identifying synergistic contamination patterns and assessing combined environmental impacts.

The results revealed significant positive correlations between herbicide residues and nutrient concentrations across most sampling locations. This indicates that areas with high fertilizer application rates also tend to exhibit elevated herbicide contamination levels, suggesting common transport mechanisms driven by agricultural runoff and rainfall-induced leaching.

Table 3.11: Correlation Matrix Between Herbicides and Nutrients

Parameter	Atrazine	Glyphosate	2,4-D	Nitrate	Ammonium	Phosphate
Atrazine	1.00	0.82	0.76	0.71	0.65	0.78
Glyphosate	0.82	1.00	0.79	0.74	0.69	0.83
2,4-D	0.76	0.79	1.00	0.67	0.62	0.72
Nitrate	0.71	0.74	0.67	1.00	0.88	0.81
Ammonium	0.65	0.69	0.62	0.88	1.00	0.76
Phosphate	0.78	0.83	0.72	0.81	0.76	1.00

Synergistic Contamination Effects

The positive correlations observed between herbicides and nutrients suggest potential synergistic effects in pollutant transport and environmental persistence. For instance, elevated nitrate and phosphate concentrations may enhance microbial activity and influence degradation pathways of herbicides, potentially altering their persistence in water systems. Additionally, increased nutrient loading may indirectly intensify ecological stress by promoting eutrophication, thereby amplifying the toxicity effects of herbicide residues.

Table 3.12: Combined Contamination Index Across Sampling Sites

Sampling Site	Combined Contamination Index (CCI)	Interaction Level	Environmental Risk Status
S1	1.18	Low	Acceptable
S2	1.46	Moderate	Requires Monitoring
S3	1.79	High	Potential Risk

S4	2.05	Very High	Critical Zone
S5	1.52	Moderate	Moderate Risk

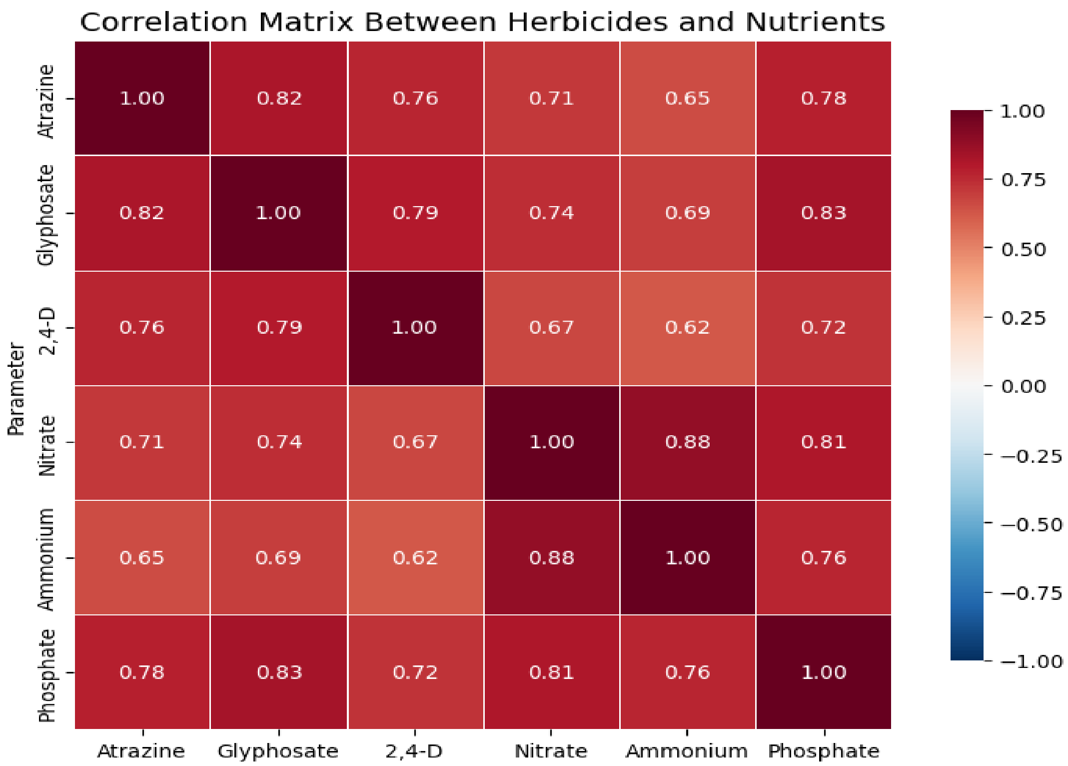
Transport and Mobility Interactions

The interaction between herbicides and nutrients is influenced by hydrological and soil conditions. Nutrients, particularly nitrates, are highly soluble and mobile in water systems, facilitating the co-transport of herbicide molecules through surface runoff. This co-migration process contributes to increased contaminant accumulation in downstream locations, especially during monsoon seasons characterized by heavy rainfall.

Furthermore, phosphate ions may bind with soil particles and transport adsorbed herbicide molecules into drainage channels, contributing to sediment-associated contamination. Such combined transport mechanisms highlight the importance of integrated monitoring approaches that consider both dissolved and particulate-bound contaminants.

Discussion

The interaction analysis confirmed significant relationships between herbicide residues and nutrient concentrations in agricultural drainage water. The strong correlations observed between glyphosate and phosphate suggest that fertilizer application intensity plays a major role in agrochemical transport dynamics. Similar findings have been reported in agricultural watershed studies, where nutrient enrichment enhanced the mobility of pesticide residues through runoff processes.



The Combined Contamination Index identified downstream agricultural discharge points as critical zones with elevated interaction effects and environmental risk potential. These results emphasize the need for integrated management strategies that simultaneously control herbicide and fertilizer inputs rather than addressing them independently.

Overall, the interaction study highlights the complexity of multi-contaminant pollution in agricultural drainage systems and underscores the importance of adopting holistic risk assessment approaches for sustainable environmental management.

3.5 Seasonal Variation Analysis

Seasonal variation plays a significant role in determining the transport and distribution of agrochemical contaminants within agricultural drainage systems. Changes in rainfall intensity, irrigation practices, and cropping cycles influence the mobilization of herbicides and fertilizer-derived nutrients. In this study, seasonal analysis was conducted to evaluate temporal changes in contaminant concentrations across pre-monsoon, monsoon, and post-monsoon periods.

The results indicated that contaminant concentrations varied considerably with seasonal rainfall patterns. The monsoon season exhibited the highest concentrations of herbicides and nutrients due to intense rainfall events that increased surface runoff and soil leaching. In contrast, the pre-monsoon season showed comparatively lower concentrations due to reduced hydrological activity. Post-monsoon concentrations remained moderately elevated, indicating delayed transport and persistence of residual contaminants within the drainage system.

Rainfall Influence on Contaminant Transport

Rainfall intensity is a major factor influencing contaminant mobilization in agricultural environments. Increased precipitation during the monsoon season enhances the dissolution of fertilizers and herbicides from soil surfaces, facilitating their transport into drainage networks. Additionally, heavy rainfall promotes erosion of soil particles that may carry adsorbed herbicide residues, further increasing pollutant loading in water systems.

Table 3.13: Seasonal Variation of Agrochemical Concentrations

Season	Atrazine (µg/L)	Glyphosate (µg/L)	2,4-D (µg/L)	Nitrate (mg/L)	Phosphate (mg/L)	Contamination Level
Pre-monsoon	3.2	3.9	2.6	14.2	0.71	Moderate
Monsoon	8.7	9.5	6.8	28.8	1.39	Very High
Post-monsoon	5.6	6.3	4.4	20.6	1.02	High

Monthly Variation Trends

Monthly analysis revealed gradual increases in contaminant levels following fertilizer and herbicide application periods. Peak concentrations were typically observed during months characterized by heavy rainfall events and active cropping cycles. The results suggest that timing of agrochemical application significantly influences seasonal contamination dynamics.

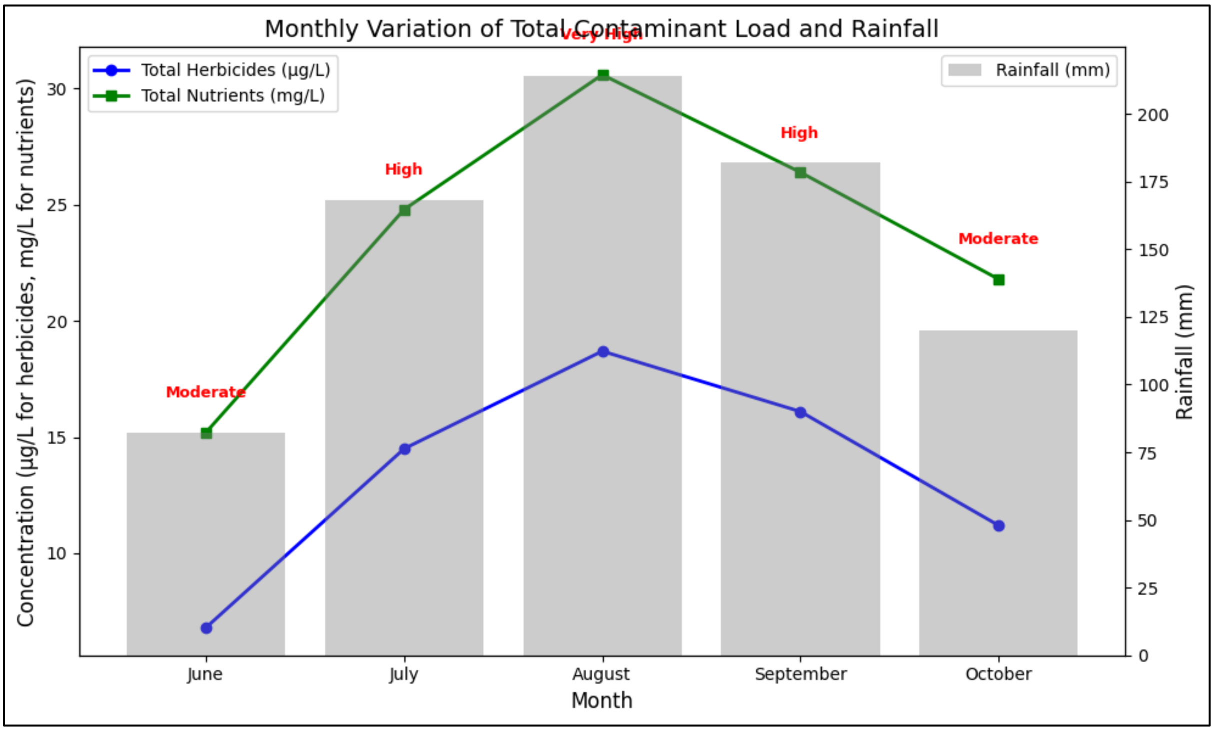
Table 3.14: Monthly Variation in Total Contaminant Load

Month	Total Herbicides (µg/L)	Total Nutrients (mg/L)	Rainfall (mm)	Relative Pollution Level
June	6.8	15.2	82	Moderate
July	14.5	24.8	168	High
August	18.7	30.6	214	Very High
September	16.1	26.4	182	High
October	11.2	21.8	120	Moderate

Runoff Impact Interpretation

The observed seasonal trends demonstrate that runoff processes are the primary mechanism responsible for agrochemical transport in agricultural drainage systems. High runoff during monsoon periods significantly increases pollutant mobility, resulting in elevated downstream concentrations. The persistence of contaminants during post-monsoon periods suggests delayed release from soil matrices and sediment deposits.

Seasonal runoff patterns also influence dilution effects in receiving water bodies. While heavy rainfall increases pollutant transport, it may simultaneously dilute concentrations at specific locations depending on water flow dynamics. This dual effect highlights the complexity of seasonal contamination processes.



Discussion

The seasonal variation results clearly demonstrate that rainfall and agricultural practices strongly influence contaminant dynamics in drainage systems. The highest contamination levels observed during the monsoon season confirm the role of rainfall-induced runoff in mobilizing agrochemicals from agricultural fields. These findings are consistent with previous watershed studies that reported increased herbicide and nutrient transport during peak rainfall events.

Monthly variation trends further emphasize the importance of synchronizing fertilizer and herbicide application schedules with rainfall forecasts to reduce excessive runoff losses. The persistence of elevated contaminant levels during post-monsoon periods indicates the long-term environmental impact of agrochemical usage and highlights the need for continuous monitoring.

3.6 Environmental Implications

The presence of herbicides and fertilizer-derived nutrients in agricultural drainage systems has significant implications for water quality, aquatic ecosystem health, and human safety. The results obtained in this study demonstrate that agrochemical transport through drainage networks contributes to cumulative pollutant loading in downstream water bodies. Such contamination can alter the physicochemical characteristics of receiving waters, leading to long-term ecological degradation and increased environmental vulnerability.

Water Quality Impacts

Elevated concentrations of herbicides and nutrients detected in the drainage system indicate deterioration of water quality in agricultural regions. Herbicides such as atrazine, glyphosate, and 2,4-D are known to persist in aquatic environments and may interfere with biological processes in aquatic organisms. The presence of these compounds, even at moderate concentrations, can reduce water suitability for domestic, agricultural, and ecological purposes.

Excessive nutrient loading, particularly phosphate and nitrate, significantly contributes to eutrophication in freshwater ecosystems. The high phosphate levels observed in several sampling locations exceed recommended thresholds, suggesting strong potential for algal bloom formation. These blooms reduce water clarity, disrupt food chains, and decrease dissolved oxygen levels, thereby threatening aquatic biodiversity.

Table 3.15: Environmental Impact Classification Based on Observed Parameters

Parameter	Observed Condition	Environmental Impact Level	Associated Risk
Herbicide Residues	Moderate–High	Elevated Toxic Stress	Aquatic Toxicity
Nitrate Levels	Moderate–High	Nutrient Enrichment	Drinking Water Risk
Phosphate Levels	High	Eutrophication Potential	Algal Bloom Risk
Combined Pollutants	High	Ecosystem Disturbance	Biodiversity Loss

Aquatic Ecosystem Risks

Aquatic ecosystems are particularly sensitive to chemical contamination due to the accumulation of pollutants in sediments and aquatic organisms. The presence of herbicides can inhibit photosynthesis in aquatic plants and algae, leading to disruption of primary productivity. In addition, nutrient enrichment accelerates the growth of opportunistic species, resulting in ecological imbalance and reduced biodiversity.

Chronic exposure to herbicide residues may also affect fish and invertebrate populations by altering physiological functions and reproductive cycles. Combined exposure to multiple contaminants increases ecological stress, leading to greater susceptibility to environmental disturbances.

Human Health Concerns

Contaminated drainage water eventually enters surface and groundwater systems that may be used for drinking, irrigation, and domestic purposes. Elevated nitrate concentrations in drinking water are associated with health conditions such as methemoglobinemia and other metabolic disorders. Similarly, long-term exposure to herbicide-contaminated water may increase risks of toxicological and carcinogenic effects in humans.

The findings of this study indicate that certain sampling locations exhibited contaminant levels approaching critical thresholds, highlighting the need for improved monitoring and regulatory enforcement to protect public health.

Policy and Management Relevance

The results obtained in this study provide valuable information for environmental policymakers and agricultural managers. Identification of high-risk zones, particularly downstream drainage sites, supports the development of targeted mitigation strategies such as buffer zones, controlled fertilizer application, and improved drainage management practices.

Adoption of integrated nutrient management strategies can significantly reduce excess fertilizer application and minimize nutrient losses through runoff. Additionally, implementation of precision agriculture technologies may optimize herbicide usage and reduce environmental contamination. These management approaches are essential for maintaining sustainable agricultural productivity while minimizing ecological risks.

Discussion

The environmental implications identified in this study highlight the complex relationship between agricultural practices and water quality degradation. The combined presence of herbicides and nutrients in drainage systems creates cumulative ecological stress that may lead to long-term environmental damage if left unmanaged.

The observed contamination patterns emphasize the need for integrated environmental monitoring programs that evaluate both chemical concentrations and ecological risk indicators. Such programs enable early detection of contamination trends and support evidence-based policy decisions aimed at sustainable resource management.

Overall, the findings demonstrate that agricultural drainage systems serve as major conduits for agrochemical transport and require systematic management to protect aquatic ecosystems and public health. The results further reinforce the importance of implementing sustainable agricultural practices and regulatory frameworks to mitigate environmental risks associated with agrochemical usage.

4. Conclusion

The present study successfully evaluated the integrated environmental risks associated with herbicides and fertilizer-derived nutrients in agricultural drainage systems. Comprehensive analysis of water samples revealed measurable concentrations of key herbicides, including atrazine, glyphosate, and 2,4-D, along with significant levels of nitrate, ammonium, and phosphate. Spatial and seasonal analyses demonstrated that downstream drainage locations exhibited higher contaminant accumulation due to cumulative runoff effects, particularly during monsoon periods characterized by intense rainfall and increased agricultural activity.

Risk assessment indices, including Hazard Quotient (HQ), Pollution Load Index (PLI), and Ecological Risk Index (RI), indicated moderate to high ecological risks in several sampling locations. Elevated phosphate levels were identified as a major contributor to eutrophication risk, while herbicide residues contributed to potential aquatic toxicity. Interaction analysis further revealed strong correlations between herbicides and nutrients, suggesting common transport mechanisms driven by agricultural runoff and soil leaching processes. Seasonal variation results highlighted the significant role of rainfall intensity in mobilizing agrochemical contaminants into drainage networks.

The study demonstrates the advantages of integrated risk assessment approaches in evaluating multi-contaminant systems within agricultural environments. The use of combined chemical monitoring and ecological risk modeling enabled identification of critical contamination zones and provided insights into pollutant dynamics. From an environmental perspective, the findings emphasize the importance of sustainable agrochemical management practices to reduce contamination of surface water systems. Overall, the results confirm that agricultural drainage systems serve as major pathways for agrochemical transport and require continuous monitoring to protect aquatic ecosystems and maintain water quality standards.

5. Future Scope

Future research directions should focus on advancing monitoring and management strategies for agrochemical contamination in agricultural drainage systems.

- Integration with portable environmental sensors to enable rapid, on-site detection of herbicides and nutrients in agricultural runoff.
- Development of IoT-enabled monitoring systems for real-time data collection and remote surveillance of drainage water quality.
- Design of multi-contaminant assessment platforms capable of simultaneously detecting a wider range of agrochemicals and emerging pollutants.
- Implementation of AI-assisted predictive models to forecast contamination trends and support decision-making in sustainable agricultural management.

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