(Online) ISSN 2712-0554
Original Research

Heritage and Sustainable Development
Vol. 7, No. 1217, 2025, pp.401-414
https://doi.org/10.37868/hsd.v7i1217.

Statistical assessment of agricultural fertilizer impacts on water quality and environmental sustainability

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Received Mar. 14, 2024
Revised Apr. 23, 2025
Accepted Apr. 30, 2025
Online May 6, 2025

Abstract

Agriculture is vital for global food production, but excessive fertilizer use poses serious risks to water quality and environmental health. Fertilizers, especially those high in nitrogen and phosphorus, can run off into nearby water bodies, causing nutrient pollution, algal blooms, and ecosystem damage. This study investigates how fertilizer use affects water quality by analyzing field data, including application rates and various water quality indicators. Water samples were collected from multiple sources over several months to account for seasonal changes and rainfall impacts. Key parameters measured included pH, dissolved oxygen, nitrate, phosphate, turbidity, organic matter, and trace metals like iron and zinc. Statistical tools—such as regression analysis, correlation studies, and multivariate techniques—were used to assess the relationship between fertilizer use and water quality. Results highlight the significant environmental impact of fertilizer runoff and emphasize the need for more sustainable management practices. These findings offer guidance for farmers, policymakers, and environmental advocates aiming to protect water resources while maintaining agricultural productivity.

Keywords: Agricultural fertilizer, Water quality, Environmental sustainability, Ecosystems, Statistical analysis

1. Introduction

Agriculture is one of the most common land use sectors, covering around 4.9 billion hectares (38% of Earth's terrestrial area). Its growth has impacted the entire biosphere and was a major factor in the sequence of physical, chemical, and biological occurrences that brought the planet's entry into the Anthropocene, a period in which human activity has a disruptive impact on the natural systems that maintain life on Earth [1]. Agriculture is widely regarded as the most serious industry affecting water resources due to its massive demand and impact on the pollution of both groundwater and surface water. Agricultural pollution is much more prevalent in some areas than pollution from industry and cities. Agricultural contamination is caused by excessive pesticide usage, inadequate postharvest and animal waste management, and traditional irrigation schemes. These practices emit nutrients, salts, pathogens, pesticides, organic matter (OM), sediments, heavy metals, and other developing pollutants into water bodies by various mechanisms, such as leaching, atmospheric deposition, runoff, and erosion, affecting their quality [2].

Fertilizers are required for agriculture to feed the world's expanding population, but overuse of chemical fertilizers pollutes the environment. Only 20–50% of fertilizers are used effectively; the remaining 50–80% are lost over time through leaching, emissions, or incorporation into the soil by microorganisms, resulting in ecological issues like decreased soil fertility and economic losses [3]. Fertilizer mineral is a global commodity that is required for the profitable development of viable crops. It's an appropriate supply that enhances soil properties and has a substantial impact on plant growth, food security, soil fertility, sustainable agriculture, and environmental growth. Fertilizers, particularly phosphorus (P) and nitrogen (N), cause both good and harmful environmental effects [4].

Agricultural fertilizer (AF) usage is broadly accepted as a main cause of water pollution. The agriculture industry has experienced a significant growth in demand for chemical fertilizers [5]. Water is an important environmental factor that controls life's existence and limits people's socioeconomic advancement. Inland and overseas surface and subsurface water schemes play an important role in daily living actions, particularly for agriculture, industry, drinking, recreation, and other public purposes. Everyday activities are dependent on accessibility and water quality (WQ). The availability of WQ for various uses is becoming increasingly challenging as a result of the rapid population increase and the rise of agro-industries [6].

WQ is critical for food production, human life, and the environment, and it becomes a cause for concern when salinization, agricultural pollution, or a lack of sufficient wastewater treatment changes water from a resource to a potential threat [7]. Assuring excellent WQ is a crucial issue around the globe as the quality of water steadily degrades due to a variety of sources, including natural, human, or both [8].

Agriculture's sustainability is vital for providing food security and reducing hunger for the world's growing population. Furthermore, weather and climate change scenarios, as well as sustainable water management in the face of water scarcity, offer substantial issues in future years [9]. Overconsumption and pollution pose serious threats to the world's water resources. Agricultural irrigated water usage accounts for 70% of the total world water extraction. Extreme water contamination results from nonpoint source pollution brought by agricultural operations [10]. The key features of the AF impacts on WQ and environmental sustainability are depicted in Figure 1.

Figure 1. AF impacts on WQ and environmental sustainability

The environmental impact of both organic and inorganic fertilizers was evaluated [11], with particular attention to contamination hazards and the impacts on soil, water, and air. The process included examining heavy metal accumulation, nutritional loss, and pollution caused by fertilizers. According to the results, using excessive fertilizer causes greenhouse gas emissions, water eutrophication, and soil deterioration. The absence of long-term data, site-specific variations, and diversity in contamination sources are some of the limitations that underscore the need for sustainable agriculture policy and improved nutrient management techniques. Nanocomposite-based fertilizers were investigated [12] as sustainable substitutes for traditional fertilizers to enhance nutrient management in agriculture. It examines different characterization and synthesis methods and how they are used in plant nutrition. Their improved efficiency, slow-release characteristics, and possible environmental advantages are highlighted by the findings. However, there are still issues with stability, environmental destiny, field effectiveness, and cost-effective synthesis. These constraints must be addressed by more research before ecologically sustainable agriculture can be widely adopted and commercialized.

The influence of intensive and organic farming methods on Lithuania's surface and groundwater quality was evaluated [13]. Water samples were taken from 23 nearby agricultural fields and five rivers using wells that were bored four to five meters deep. The findings indicated that compared to intensive farms, organic farms had lower amounts of pH, total N, total P, NO_3^--N, NH_4^+-N, and PO_4^{3-}-P. A drawback is that just a small number of groundwater locations were examined, which could restrict more extensive generalizations. To investigate sustainable alternatives, the research [14] evaluated the environmental effects of nitrogenous fertilizers. To assess methods such as slow-release fertilizers, organic manure, and fertilizers with nanotechnology, the research conducts a thorough literature analysis. The findings show that these substitutes can preserve agricultural yields while lowering nitrogen emissions. However, issues include insufficient knowledge of new agricultural techniques, concerns about food security, and small-scale farmers' limited financial resources. Even with these drawbacks, it is imperative to replace overly nitrogenous fertilizers to maintain long-term environmental sustainability.

The contribution of nanofertilizers (NFs) to improving agricultural yield and environmental sustainability was assessed [15]. A thorough analysis of different NFs, how they are applied, and how they affect soil health, plant development, and environmental quality was carried out. Results show that NFs lessen their negative effects on the environment while increasing yield, stress tolerance, and nutrient usage efficiency. Subsequent research is necessary for safe and sustainable agricultural uses since supra-optimal concentrations have the potential to damage ecosystems and have unknown long-term impacts on human health. Global fertilizer inefficiencies and their effects on food security and the environment were evaluated [16]. It reveals geopolitical and economic inequalities and detects nutritional imbalances, especially in the usage of nitrogen (N), phosphorus (P), and potassium (K). The findings indicate that either excessive or insufficient fertilizer causes pollution, degrades soil, and endangers biodiversity. Among the limitations are regional variations in data and changing farming methods.

The integration of contemporary technology with organic techniques to increase sustainability and production was assessed [17]. Results from a comparison of conventional and organic farming practices show that while initial yields are lower, soil health and food quality are greater. High expenses, work intensity, and scalability problems are some of the drawbacks. These issues can be resolved by developing creative methods, which will promote an agricultural system that is more robust and environmentally benign. As an environmentally benign substitute for artificial fertilizers, the investigation [18] assessed how well biofertilizers improved soil nutrients and supported sustainable agriculture. The process entails examining microbial processes, including hormone synthesis, nutrient solubilization, and nitrogen fixation. The findings show that biofertilizers greatly increase soil fertility and plant development. Limitations, however, include the requirement for optimum application tactics to maximize their advantages in various agricultural contexts and the unpredictability in microbial performance under various climatic circumstances. By examining agroecological, organic, biodynamic, regenerative, urban, and precision agricultural practices, the research [19] investigated sustainable food systems.

It evaluates important sustainability concerns pertaining to food, climate change, the environment, resource utilization, and rural growth through a methodical literature analysis. The results emphasized the need to switch to robust, low-impact food production techniques. However, obstacles to adoption, financial limitations, and policy shortages are significant challenges. The report emphasized the necessity of comprehensive, long-term approaches to improve food security and reduce environmental damage. In rice cultivation, the research [20] evaluated the economic, agronomic, and environmental sustainability of using controlled release nitrogen fertilizers (CRNF) instead of urea. Four fertilization techniques were tested in a one-year field research, with economic indicators, nitrogen usage efficiency (NUE), and emergency accounting used for assessment. The results indicated that CRNF enhanced economic advantages (5.21–11.44%), NUE (30.65–43.96%), and sustainability (2.82–4.61%), with the 60% CRNF + 40% urea scheme (N3), exhibiting the highest performance. The necessity for wider validation and regional specificity is among the limitations.

The potential of nano-enabled fertilizers to improve crop nutrition and sustainability was investigated [21]. Recent research on the creation, use, and interactions of nanofertilizers with food plants is analyzed as part of the technique. The findings show that nanofertilizers increase agricultural output, abiotic stress tolerance, and nutrient efficiency. However, there are drawbacks, such as possible toxicity, expensive manufacturing, and difficult regulations. Notwithstanding these limitations, nano-biotechnology offers a viable strategy for creating intelligent and sustainable agriculture by maximizing nutrient delivery and reducing environmental effects. The contribution to enhancing plant development and stress tolerance was assessed [22]. Recent developments in NF applications were examined in systematic research, which also highlighted how effective they are at reducing stress and delivering nutrients. The outcomes show increased environmental sustainability and yield. However, there are drawbacks, such as exorbitant expenses, possible toxicity, and regulatory issues. Future analyses should evaluate long-term effects and adjust formulations for sustainable farming methods.

Global trends in freshwater nitrate contamination brought by rising fertilizer nitrogen (N) use, especially in emerging nations, were evaluated [23]. N usage, leaching, and legacy impacts are examined using data from the last 20 years. Results show that crops consume less than half of the nitrogen that is applied, and the buildup of soil over time contributes to pollution. Although isotopic analysis and simulation models help to understand sources, they have drawbacks such as complicated soil-water interactions and unclear long-term mitigation efficacy predictions. Using NH3N as an indicator, the research [24] evaluated the impacts of agricultural non-point source pollution on river WQ. 18 state-controlled monitoring sites and 46 prefecture-level cities were included in the panel data analysis. The findings indicate that overuse of fertilizer exacerbates pollution and has transboundary impacts in locations downstream. Long-term lagged effects and threshold effects were found. Potential data errors and unconsidered outside influences are among the limitations. The results point to coordinated agriculture strategies and inter-basin collaboration as ways to reduce pollution.

Nitrogen and phosphorus contamination were the main goals of [25], which evaluated nutrient water pollution from unsustainable farming methods. According to research, water bodies continue to have excessive nutrient concentrations, which can cause eutrophication and pose health hazards. Although regulations are in place, they differ in their efficacy. Regional variations in data and changing farming methods are among the limitations. The report emphasizes that to reduce pollution, more enforcement and sustainable farming practices are required. The influence of the WF link with crop quality in controlling rocky desertification was evaluated [26]. It finds research trends, theoretical developments, and gaps by examining 427 publications. The majority of research was conducted in dry locations, and the results show an "S" curve rise in publications. However, there is very little research being done in karst regions. Emphasizing the requirement for validation in karst environments, the research draws attention to theoretical and technological shortcomings. Region-specific applicability and a lack of research on dynamic models are among the limitations.

To support resource management and conservation, the combined effects of human and natural variables on stream WQ metrics were examined [27]. It identifies important factors affecting WQ and their impacts on biota through a methodical assessment of the literature and data analysis. The findings showed temporal and regional differences in the determinants of WQ. The necessity for integrated, multi-scale management techniques is highlighted by the constraints, which include unpredictable data, a lack of long-term research, and complications in identifying certain factor contributions. Agrochemical contamination was analyzed at both temporal and geographical scales in [28] to evaluate the WQ in the river. In both the rainy and dry seasons, 183 water samples were taken every two weeks and examined for 39 different characteristics, such as minerals, pesticides, and heavy metals. Ten pesticides were found to be over the legal levels, while heavy metals were not found. The rainy season was when contamination peaked, with seasonal variations. Limitations include the possible underestimation of pollution sources and the absence of long-term monitoring.

Using WHO and TSWQR criteria, the research [29] examined variations in the WQ of seven main rivers over time. Multivariate statistical techniques were utilized to determine the sources of pollution and the connections between the parameters. The findings showed both point and non-point causes of contamination, and several streams had medium levels of fluoride and NO2-N in their water. Irrigation indicators stayed within safe bounds despite a minor alkalinity. However, because of continued human activity, future anthropogenic repercussions are still unknown. The effectiveness of the river chief scheme in reducing the agricultural non-point source (NPS) pollution was assessed [30]. Based on empirical research and panel data from 308 counties, the research concludes that while the method reduces water pollution caused by manure, it is useless in reducing pollution caused by fertilizers. River chiefs only collaborate inside their respective regions, which limits their ability to have a wider influence. The report emphasized the necessity of better cross-provincial cooperation and more robust fertilizer management. Potential data limitations and unconsidered external environmental elements are examples of limitations.

The research aims to conduct a statistical analysis of the effects of AF on WQ and environmental sustainability.

2. Materials and methods

The research employed a comprehensive approach to evaluate the influence of fertilizer runoff on WQ. In this section, water sampling points, WQ sampling, and statistical analysis were explained.

2.1. Water sampling points

During the planting season, twelve water samples were taken between three to seven days following fertilization, excluding the initial and final samples. 17 sampling locations were chosen for this research to measure fertilizer runoff from drainage systems, agricultural fields, irrigation canals, and major canals. These sample sites guaranteed thorough coverage of the various water sources impacted by the usage of fertilizers.

2.2. Water quality (WQ) sampling

A multiparameter probe was used to monitor the physical WQ parameters in situ, such as pH, dissolved oxygen (DO), and temperature. To guarantee precision, each parameter was recorded three times for each sample point. To ensure constant environmental conditions, sampling was executed between 9:00 AM and 11:00 AM. To guarantee accuracy, all sensors were calibrated against reference solutions prior to field sampling. HDPE bottles that had been pre-soaked in hydrochloric acid (HCl) for a full day and washed with deionized water to remove any contaminants were used to manually collect water samples for laboratory examination. While samples for biochemical oxygen demand (BOD) measurement were taken in glass amber bottles to avoid light exposure, surface water samples were taken straight from water bodies. To ensure accuracy, each sample was taken in triplicate. Samples were stored in an ice-filled cooler box throughout transit, and they were then kept at 4°C in the lab for 48 hours before being analyzed. Prior to testing, samples were allowed to come to room temperature for two hours. Nitrate (NO_3^-), nitrite (NO_2^-), phosphate (PO_4^{3-}), chloride (Cl^-), sodium (Na^+), OM, suspended particles, turbidity, chemical oxygen demand (COD), and trace metals (Fe, Mn, Cu, Zn, Al, K, Mg) were among the important WQ metrics that were examined. Within 28 days of sample collection, inductively coupled plasma (ICP) was utilized to analyze the trace metals. The analytical methods for chemical analysis are represented in Table 1.

Table 1. Analytical methods for chemical analysis in the laboratory

Parameter	Method	Equipment Used
Electrical Conductivity (μS/cm)	Conductivity Probe	YSI Pro DSS, USA
pH	Electrometric Method	pH Meter (Hanna Instruments)
Dissolved Oxygen (DO) (mg/L)	Membrane Electrode Method	YSI Pro ODO, USA
Nitrate (NO_3^-) (mg/L)	Cadmium Reduction	HACH 3900 Spectrophotometer, USA
Nitrite (NO_2^-) (mg/L)	Colorimetric Method	HACH 3900 Spectrophotometer, USA
Chloride (Cl^-) (mg/L)	Argentometric Titration	Digital Titrator (HACH, USA)
Sodium (Na^+) (mg/L)	Flame Photometry	Flame Photometer (Sherwood)
Phosphate (PO_4^{3-}) (mg/L)	Ascorbic Acid Method	HACH 3900 Spectrophotometer, USA
Organic Matter Content	Loss on Ignition	Muffle Furnace (Thermo Fisher)
Chemical Oxygen Demand (COD) (mg/L)	Reactor Digestion	Digester Reactor DRB 200, USA
Suspended Solids (mg/L)	Gravimetric Method	Filtration Apparatus
Turbidity (NTU)	Nephelometric Method	HACH 2100P Turbidimeter, USA
Color (Pt-Co Units)	Platinum-Cobalt Method	HACH 3900 Spectrophotometer, USA
Iron (Fe) (mg/L)	Atomic Absorption Spectrometry (AAS)	PerkinElmer AAnalyst 400
Manganese (Mn) (mg/L)		
Copper (Cu) (mg/L)		
Zinc (Zn) (mg/L)		

2.3. Statistical analysis

To evaluate the relationship between fertilizer application and changes in WQ, the gathered data were statistically examined using multivariate approaches, regression models, correlation analysis, and descriptive statistics using the SPSS software 30.0. To find patterns in fertilizer-induced pollution, descriptive statistics use metrics like mean, standard deviation, and range to summarize data on WQ. Regression models generate connections between fertilizer application rates and important WQ indicators like phosphate and nitrate concentrations. Correlation analysis quantifies the strength and direction of associations between different WQ parameters, such as the effect of chloride levels on electrical conductivity, while multivariate techniques are used to classify water samples, detect pollution patterns, and identify dominant contamination sources, thereby assisting in sustainable fertilizer management strategies.

2.4. Classification of water quality (WQ)

The WQ data collected for this research were classified using the National WQ Standards (NWQS), which identify water bodies based on contamination levels. The classification is divided into six groups (Class I, IIA, IIB, III, IV, and V) based on WQ, in declining order.

Class I water is pristine and acceptable for drinking without treatment.
Class IIA: Suitable for human consumption following routine treatment.
Class IIB: Allows for recreational usage with bodily contact.
Class III is suitable for animal drinking and irrigation.
Class IV is suitable for industrial water supply, but requires significant treatment.
Class V water is highly contaminated and unfit for any use.

3. Results

The data gathered was analyzed using statistical methods, such as descriptive statistics, regression models, correlation analysis, and multivariate approaches, to examine the influence of fertilizers on WQ and surrounding ecosystems.

3.1. Assessment of fertilizers on water quality and surrounding ecosystems using descriptive statistics

Descriptive statistics describe and assess significant characteristics connected to agricultural fertilizer usage, including its influence on water quality and environmental sustainability. It aids comprehension of distributions by providing measurements such as mean, minimum values, standard deviation ($Std.Dev$), and maximum values. The mean values reflect the average distribution of parameters such as total population, farmers, and various agricultural techniques, including the use of chemical and organic fertilizers. The standard deviation illustrates data variability, indicating rises in farm size, water consumption trends, and soil composition. The data range is defined by its minimum and maximum values, which show the range of variance among agricultural factors such as small-scale farms and the amount of rainfall per year. These statistics are critical for assessing trends in fertilizer application and its relationship to water quality and environmental sustainability, assisting researchers and policymakers in identifying critical risk factors, optimizing resource management, and developing sustainable agricultural practices that reduce negative environmental impacts. The outcomes of the descriptive statistics are illustrated in Table 2 and Figure 2.

Table 2. Outcomes of descriptive statistics

Variables	Mean	Std. Dev.	Min	Max
Total Population	50,000	2,500	47,000	53,000
Farmers (%)	65.00%	4.50%	60.00%	70.00%
Chemical Fertilizer Usage (%)	75.00%	5.20%	68.00%	82.00%
Organic Fertilizer Usage (%)	25.00%	3.80%	20.00%	30.00%
Small-Scale Farms (%)	60.00%	6.10%	50.00%	68.00%
Medium-Scale Farms (%)	30.00%	4.30%	25.00%	35.00%
Large-Scale Farms (%)	10.00%	2.00%	7.00%	13.00%
Groundwater Usage (%)	40.00%	5.50%	33.00%	47.00%
Surface Water Usage (%)	35.00%	4.80%	28.00%	42.00%
Rainwater Collection (%)	15.00%	2.70%	11.00%	19.00%
Irrigation Channel Usage (%)	10.00%	2.00%	7.00%	13.00%
Annual Rainfall (mm)	1,200.00	110.00	1,050.00	1,350.00
Sandy Soil Coverage (%)	30.00%	3.50%	25.00%	35.00%
Clayey Soil Coverage (%)	40.00%	4.20%	34.00%	46.00%
Loamy Soil Coverage (%)	30.00%	3.10%	26.00%	34.00%

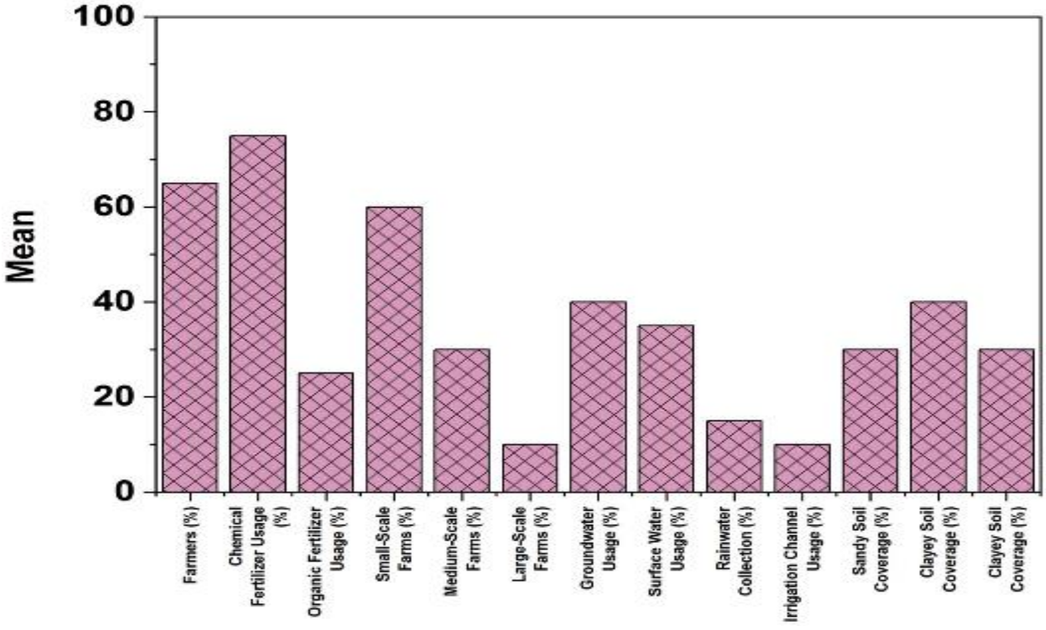

Figure 2. Graphical representation of the descriptive statistics

Table 2 shows that the entire population has a $mean$ of 50,000 and a $Std.Dev$ of 2,500, ranging from 47,000 to 53,000. Farmers represent around 65% of the population, with a fluctuation of 4.5%. Chemical fertilizer use is 75%, with a range of 68% to 82%, whereas organic fertilizer use is 25%. Small-scale farms account for 60% of all farms, ranging from 50% to 68%, while medium and large farms contribute 30% and 10%, respectively. Variations in soil cover, rainfall, and water sources all affect the evaluation of WQ.

3.2. Assessment of fertilizers on water quality and surrounding ecosystems using regression models

Regression models establish associations between parameters and WQ indicators, allowing for the prediction of pollutant levels depending on input factors. Multiple linear regressions were used to determine how nitrate, phosphate, and OM contents change in relation to fertilizer application, rainfall, and soil conditions. These models estimate the extent to which fertilizer runoff impacts WQ, allowing for a more accurate environmental risk assessment. The regression coefficient (β) assesses the influence of fertilizer application on WQ measures, showing its size and direction. Standard error (SE) is a measure of β's accuracy, indicating variability due to sample variations. The $t-value$ assesses the significance of β, indicating how fertilizer impacts WQ. A $p-value < 0.05$ suggests a significant association. The R^2 (coefficient of determination) measures how fertilizers and environmental variables impact WQ. Finally, policymakers and farmers can use the data to establish sustainable fertilizer methods that reduce pollution and protect water resources. The outcomes of the regression model are illustrated in Table 3.

Table 3. Outcomes of the regression model

Water Quality Parameter	Independent Variables	β	SE	$t-value$	$p-value$	R^2	Interpretation
EC	pH, Na^+, Cl^-	0.28, 0.14, 0.35	0.06, 0.05, 0.04	4.67, 2.80, 8.75	<0.001, 0.006, <0.001	0.75	Positive correlation with salinity-related parameters.
pH	NO_3^-, Rainfall (mm)	-0.25, 0.18	0.07, 0.06	-3.57, 3.00	<0.001, 0.004	0.60	Nitrate decreases pH, rainfall slightly increases it.

Water Quality Parameter	Independent Variables	β	SE	$t - value$	$p - value$	R^2	Interpretation
DO	NO_3^-, Temperature (°C)	-0.38, -0.45	0.11, 0.10	-3.45, -4.50	<0.001, <0.001	0.55	Higher NO_3^- and temperature reduce dissolved oxygen.
NO_3^-	Fertilizer Rate (kg/ha), Rainfall (mm)	0.45, 0.30	0.12, 0.08	3.75, 3.75	<0.001, <0.001	0.68	Fertilizer and rainfall increase nitrate runoff.
NO_2^-	OM, Fertilizer Rate (kg/ha)	0.27, 0.20	0.09, 0.07	3.00, 2.86	0.004, 0.005	0.62	Nitrite increases with OM and fertilizers.
Cl^-	EC, Na^+	0.40, 0.35	0.08, 0.06	5.00, 5.83	<0.001, <0.001	0.73	EC and sodium strongly influence chloride levels.
(Na^+	Rainfall (mm), Irrigation Source	0.18, 0.22	0.07, 0.05	2.57, 4.40	0.012, <0.001	0.65	Rainfall and irrigation affect sodium concentration.
PO_4^{3-}	Rainfall (mm), OM, Fertilizer Rate (kg/ha)	0.32, 0.18, 0.22	0.10, 0.08, 0.09	3.20, 2.25, 2.44	0.003, 0.027, 0.018	0.63	Phosphate levels rise with rainfall, OM, and fertilizers.
OM	SS, PO_4^{3-}	0.48, 0.30	0.11, 0.09	4.36, 3.33	<0.001, 0.002	0.71	OM is positively correlated with SS and phosphate.
COD	Fertilizer Rate (kg/ha), OM	0.60, 0.35	0.15, 0.10	4.00, 3.50	<0.001, 0.001	0.78	Higher fertilizer application and OM increase COD.
SS	OM, NO_3^-	0.53, 0.22	0.09, 0.07	5.89, 3.14	<0.001, 0.002	0.72	SS increases with OM and nitrate levels.
Turbidity	Rainfall (mm), Phosphate PO_4^{3-}, SS	0.40, 0.25, 0.38	0.11, 0.09, 0.08	3.64, 2.78, 4.75	<0.001, 0.005, <0.001	0.69	Rainfall, phosphate, and SS contribute to turbidity.
Color	COD, PO_4^{3-}, Iron (Fe)	0.45, 0.28, 0.30	0.13, 0.11, 0.12	3.46, 2.55, 2.50	<0.001, 0.014, 0.016	0.66	Water color is influenced by COD, phosphate, and Fe.
Trace Metals	Rainfall (mm), OM, EC	0.38, 0.27, 0.25	0.09, 0.08, 0.07	4.22, 3.38, 3.57	<0.001, 0.002, 0.001	0.74	Rainfall, OM, and EC strongly impact trace metal levels.

Table 3 shows that EC has a positive correlation with Na^+ (β = 0.14) and Cl^- (β = 0.35), with an R^2 of 0.75. pH is controlled by NO_3^- ($\beta = -0.25, p < 0.001$) and rainfall ($\beta = 0.18, p = 0.004$), with a R^2 of 0.60. DO declines at increased NO_3^- levels (β = -0.38) and temperatures (β = -0.45, R^2 = 0.55). Fertilizer rate resulting in higher NO_3^- levels ($\beta = 0.45, R^2 = 0.68$). COD levels increase with fertilizer use ($\beta = 0.60$) and OM ($\beta = 0.35, R^2 = 0.78$), indicating a significant fertilizer influence.

3.3. Assessment of fertilizers on water quality and surrounding ecosystems using correlation analysis

Correlation analysis investigates the degree and direction of connections between WQ measurements, revealing important interactions between factors including nitrate, dissolved oxygen, and turbidity. For example, a high negative association between dissolved oxygen and nitrate levels indicates eutrophication caused by fertilizer runoff. Researchers identify pollution sources by using Pearson or Spearman correlation coefficients. This strategy helps to prioritize which pollutants require rapid management attention. In the research, environmental conditions and fertilizer application impact connected WQ metrics that are identified using multiple correlation analysis (MC). Correlation with electrical conductivity (EC) measures the effect of fertilizer-induced dissolved ions on water salinity and conductivity levels. Correlation with OM measures the connection between fertilizer-induced nutrient loads and OM division in water bodies, and correlation with rainfall depth (R) measures the impact of rainfall on nutrient transport and dilution, which impacts pollutant dispersion and overall WQ as illustrated in Table 4.

Table 4. Outcomes of the correlation analysis

Sample Type	MC	EC	OM	R
Wells	EC–Cl^-–Na^+–NO_3^-–DR	Cl^-–Na^+–NO_3^-–DR	Cl^-–Na^+–NO_3^-–NO_2^-–NH_4^+–EC–DR	EC–Cl^-–NO_3^-–NH_4^+–DR
	Color–COD–OM–SS–Turbidity–Fe–Zn	Color–OM–COD–DO–pH	SS–Color–COD–Turbidity–PO_4^{3-}–DO–pH	Mn–pH–Color
	Fe–Mn–Zn–Cu	SS–PO_4^{3-}–NO_2^-–NH_4^+	NH_4^+–DO–Fe	PO_4^{3-}–Turbidity–Fe–Zn
Conduits	Cl^-–Na^+–NO_3^-–NO_2^-–NH_4^+–DR–Turbidity–DO–pH	Cl^-–Na^+–NO_3^-–NO_2^-–NH_4^+–DR	Color–COD–OM–NO_2^-–NH_4^+–Na^+–Fe–Mn–Zn–Turbidity–pH	SS–Color–COD–Turbidity–PO_4^{3-}–DO–pH
	Fe–Mn–Zn–Cu	Fe–Mn–Zn	SS–PO_4^{3-}–NO_2^-–NH_4^+–DO	PO_4^{3-}–Turbidity–Fe–Mn–Zn
Rivers	EC–NO_3^-–pH–Zn–Cl^-	Na^+–NO_3^-–NO_2^-–DR	Color–OM–Turbidity–COD	Color–COD–DO–Turbidity
	Cl^-–Na^+–NO_2^-–Fe–Color–OM–SS	Fe–Mn–Zn–pH–Turbidity	Fe–Zn–Mn–Cu–Cl^-	Mn–pH–NO_3^-–Na^+–SS
	Color–COD–SS–DR–Turbidity–Fe–Zn	NO_3^-–NO_2^-–Na^+–NH_4^+	SS–COD–PO_4^{3-}–Cl^-	PO_4^{3-}–OM–Zn–Mn

Table 4 shows that EC corresponds with Cl^-, Na^+, and NO_3^-, whereas OM correlates with COD, color, and pH in wells. In conduits, EC is significantly correlated with NO_3^- and NH_4^+, while OM is associated with COD and turbidity. In rivers, EC corresponds strongly with NO_3^- and Zn, while OM connects with turbidity and color. Rainfall affects phosphate, iron, and suspended particles, underscoring its importance in nutrient mobilization.

3.4. Assessment of fertilizers on water quality and surrounding ecosystems using multivariate techniques

Multivariate methods that simplify data and reveal hidden patterns in fluctuations in WQ include principal component analysis (PCA), canonical correspondence analysis (CCA), and factor analysis (FA). PCA can group comparable data and identify important pollution indicators, which aids in determining the pollutants' sources. Cluster analysis (CA) helps categorize areas with different fertilizer impacts by grouping water samples according to pollution levels and nutrient content. By separating fertilized from non-fertilized locations and identifying prevalent pollutants, discriminant and factor analysis (DA & FA) find relationships between variables. Through the integration of several factors into a single analytical framework, these methods aid in the holistic management of WQ. The outcomes of the multivariate methods are illustrated in Table 5.

Table 5. Outcomes of multivariate analysis

Sample Type	PCA	CA	DA & FA	CCA
Wells	Identified EC, NO_3^-, and Cl^- as dominant factors influencing water quality	Grouped samples based on EC and NO_3^- levels	FA revealed a strong correlation between Turbidity, COD, and OM	Linked fertilizer application to water quality shifts
Conduits	Identified Na^+, NO_3^-, and PO_4^{3-} as main pollution contributors	Grouped samples based on nutrient composition	DA differentiated between fertilized and non-fertilized sites	Showed a strong seasonal impact on NO_3^- and EC fluctuations
Rivers	Showed seasonal rainfall impact on NO_3^- and EC variations	Separated samples based on nutrient loading intensity	FA highlighted key contaminants influencing WQ trends	Indicated agriculture-driven WQ degradation patterns

Table 5 shows that the PCA reveals EC, NO_3^-, and Cl^- as key WQ factors in wells, whereas Na^+ and PO_4^{3-} dominate in conduits. CA categorizes samples in wells based on EC and NO_3^- levels, and in rivers based on nutrient loading intensity. Turbidity, COD, and OM are all major contributors to pollution, according to DA and FA. CCA relates fertilizer application rates to changes in WQ, demonstrating seasonal and agricultural effects.

4. Discussion

The findings demonstrate the significant influence of AF consumption on WQ and environmental sustainability, underlining the critical necessity for sustainable management techniques. Statistical analysis, using regression models and multivariate approaches, indicated high connections between fertilizer application and important WQ metrics such as NO_3^-, PO_4^{3-}, EC, COD, and turbidity. Rainfall further exacerbates nutrient discharge. PCA and FA found NO_3^-, Cl^-, and Na^+ as major drivers in water pollution, whereas CCA related seasonal changes and fertilizer application to WQ degradation. The findings show that heavy fertilizer usage contributes to eutrophication, algal blooms, and trace metal accumulation, threatening aquatic ecosystems and drinking water supplies. Cluster analysis differentiated fertilized and non-fertilized regions, highlighting the importance of agricultural activities in driving WQ patterns. These findings highlight the importance of integrated water and nutrient management measures, including precision fertilization, controlled irrigation, and organic amendments, in reducing negative environmental consequences while preserving agricultural output. Implementing evidence-based regulations and raising farmers' knowledge can assist in finding a balance between food security and environmental protection.

5. Conclusions

The statistical analysis demonstrated that agricultural fertilizer application significantly alters key water quality indicators, particularly NO_3^-, PO_4^{3-}, and COD, with strong correlations to fertilizer rates and environmental factors such as rainfall. Multivariate analyses further identified EC, NO_3^-, and Cl^- as dominant pollutants, reflecting the systemic nature of agricultural runoff and its seasonal variability. These findings emphasize the urgent need for comprehensive nutrient management strategies, including precision fertilization, integrated water governance, and farmer education programs. Despite limitations related to regional variability and short-term data collection, this study establishes a solid foundation for future investigations into optimizing fertilizer use while safeguarding ecological health. Advancing these initiatives will be essential to ensure the sustainability of both agricultural productivity and water resources.

Declaration of competing interest

The authors declare that they have no known financial or non-financial competing interests in any material discussed in this paper.

Funding information

No funding was received from any funding organization.

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