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Environmental Impact of Over-Fertilization in Rice Cultivation: A GIS-Based Spatial Risk Analysis

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Abstract: Over-fertilization in rice cultivation presents a significant environmental threat, contributing to nutrient leaching, groundwater contamination, eutrophication of aquatic ecosystems, and long-term soil degradation. This study employed a GIS-based spatial risk analysis to assess the environmental impact of fertilizer overuse across major rice-growing regions. By integrating multi-source spatial data—including fertilizer application rates, soil types, topography, and hydrological proximity—we identified critical hotspot zones and quantified regional vulnerability to nutrient-driven ecological degradation. The results revealed that southern and western regions exhibit the highest fertilizer input, particularly nitrogen and phosphorus, which correlates with elevated risk indices for runoff and leaching. Soil analysis showed that sandy soils, with poor nutrient retention capacity, intensified the environmental risk in these areas. Groundwater analysis indicated that nitrate concentrations in the East and North approached or exceeded WHO safety limits, signifying acute contamination. The risk of eutrophication at the catchment level was greatest in regions C3 and C5, shown by increased phosphorus loading and chlorophyll-a levels. GIS-based hotspot mapping highlighted zones Z1 and Z3 as essential intervention locations due to their elevated composite environmental risk. A regression analysis of fertiliser input and crop output revealed diminishing returns on nitrogen application, underscoring economic inefficiencies and environmental detriment. These findings highlight the necessity for precise fertilisation, sustainable nutrient management strategies, and focused policy actions. The research illustrates the effectiveness of GIS as a decision-support instrument in pinpointing high-risk areas and directing region-specific environmental management approaches for sustainable rice farming.

Keywords: “Over-Fertilization”, “Rice Cultivation”, “GIS Analysis”, “Nutrient Runoff”, “Eutrophication”, “Groundwater Contamination”.

INTRODUCTION

A lot of fertilisation in rice farming usually leads to water quality degradation, less biodiversity and possible health risks (Flor et al., 2021). Despite the regular appearance of rice fields, they act as habitats for many species of aquatic plants, benthic invertebrates and vertebrates (Choi et al., 2021). The unnecessary use of nitrogen and phosphorus fertilisers disturbs the delicate nature of these ecosystems and starts a chain of damaging effects according to Mitra et al. (2023). Because people around the globe are increasing in number, farmers are applying more fertiliser, often above the needed levels for rice (Wang et al., 2020). Overusing pesticides leads to problems with the economy and serious environmental damage (Tripathi et al., 2020). Rice farming that uses too much fertilizer badly affects both water and land environments, according to Bwire et al. (2024). Too much nitrogen and phosphorus fertilizer can throw off the balance in these ecosystems and cause many bad outcomes. Nitrogen pollutants may get into groundwater which can harm both our drinking water supply and human health. As a result of surface runoff, nutrients gathered on the surface are carried by rivers, lakes and coastal waterways which often leads to eutrophication (Carmona et al., 2021). Eutrophication causes too many algae to grow, resulting in less oxygen in water which creates areas where marine organisms can’t breathe.

Excessive application of fertilizers leads to eutrophication and declines water quality, threatening health for people and nature. Such a high amount of nutrients from algal blooms often causes them to produce chemicals that endanger the quality of water used for drinking and can endanger people and animals (Suffian et al., 2021). Still, if algal biomass is destroyed, it can reduce oxygen levels enough to cause death in fish and other aquatic lifeforms (Razak et al., 2021). Over-fertilization in aquatic environments is known to cause serious changes to food webs, influence the kinds of species in the environment and reduce biodiversity. GIS is a useful method for understanding where rice could be endangered by over-fertilizing (Prayogo et al., 2021). Analysis with GIS technology identifies areas with large fertiliser application amounts, after considering how different soils, terrains and nearby water bodies could be harmed. This allows for better creation of tailored ways to save fertiliser and reduce harm to the environment.

Some problems that can happen when too much fertiliser is used in rice farming are water contamination, soil worsening and more air pollution. Any surplus of nitrogen or phosphorus in farming can contaminate ground and surface water which in turn makes drinking water supplies unsafe and causes lakes and rivers to become eutrophic (Çakmakçı et al., 2023). When aquatic ecosystems are enriched by nutrients, it causes algae and aquatic vegetation to grow excessively which we call eutrophication (Sidabutar et al., 2020). Because of this, oxygen in water can get lower which can lead to the death of fish and other organisms (McLaughlin et al., 2021). If there is too much ammonia, it can stop fish from growing or might even cause death (Chenyambuga et al., 2020). If there is too much nitrogen in the soil, it can be changed into nitrous oxide which is a greenhouse gas that increases climate change. As a result, we must pay attention to environmental management by trying to lower pollutants and use biologically healthier fertilisers such as azolla in rice farms or substitute a portion of the chemical fertiliser used (Al-Bdairi & Kamal, 2021).

Managing the environmental effects of over-fertilization requires an inclusive strategy that uses sustainable farming, new technologies and policies. New ways to apply nutrients can boost the uptake of nutrients by rice plants, as well as limit the amount of these nutrients lost to the environment (Victory et al., 2020). Optimal use of fertiliser, timed for the best results and applied in the right proportions, is the main principle of precision fertilisation. With slow-release fertilisers, the nutrients are provided slowly to avoid nutrients from flowing away or running into water sources. Furthermore, making corners of circular economy, using rice by-products in biopackaging and other jobs, reduces rice farming's influence on the environment (Sousa et al., 2023). If we promote farming methods such as wet-dry cycling and rice intensification, farmers could reduce their fertiliser use and better manage water resources (Mohapatra et al., 2023). A new approach is to simply adjust the rate of fertiliser application to replace only what is removed by harvest and organic fertilisation which may reduce the harm from applying too much (Iddris et al., 2023).

The availability of GIS technology allows researchers to effectively find and illustrate regions likely to receive too much fertilizer in rice farming. With GIS, several maps such as those showing soils, the types of land use, hydrological data and fertiliser records, are blended to estimate the risk of nutrient leaching. When these statistics are combined and looked at with spatial analysis, it becomes clear which areas face high rates of fertiliser use, have vulnerable soils and risk eutrophication of nearby aquatic ecosystems. With spatial data, authorities can decide where and how decreasing fertiliser application and minimising environmental harm should happen. Decision-making technologies that use data can aid in making sound national rice supply policies (Doliente & Samsatli, 2020).

The use of both integrated soil fertility management and soil conservation technologies increases rice output (Rodriguez, 2020). In addition, these benefits let farmers make better use of fertilisers to boost their crops and lessen any negative environmental impact (Ariani, 2021 and Lawrencia et al., 2021). Bringing in sustainable farming methods, improving technology and applying regulations reduce the adverse effects of over-fertilization and help secure the ongoing sustainability of rice crops. Emphasising the pragmatic approach to hybrid rice and selecting the best sowing periods are both ways to improve rice harvesting (Ahmed & Saikia, 2020). Managing water supply and drainage by regulation can prevent your soil from becoming waterlogged and help improve air circulation (Shrestha et al., 2020).

RESEARCH METHODS

The researchers used a GIS system to analyze the environmental effects of using too many fertilizers in rice farming, by highlighting regions at greatest risk of nutrient runoff, leaching and eutrophication. For this research, multi-source data such as fertilizer maps, land classification statistical data, maps of land use, landscapes and proximity to water bodies were used. We examined surface water movements using satellite information and DEMs to assess how neighborhoods' heights make them more or less susceptible to flooding. Data on how much fertilizer is applied was gathered from agriculture departments and surveys with farmers and was then placed over spatial layers in ArcGIS Pro to find out where nutrients are loaded most. The texture and permeability of the soil were mapped to predict where nutrients might stay or move and watershed and drainage information were used to follow how nutrients pass into nearby water systems. To see which parts of the land had critical pressure from too much fertilizer, we applied hotspot analysis and weighted overlay techniques. Additionally, using regression and correlation analyses, we investigated how changes in fertilizer use were related to risks of eutrophication and high levels of nitrate in the groundwater. Water and soil from five hotspots were sampled during field validation to measure actual nutrient levels and validate the model estimates. This analysis was summarized with thematic maps of vulnerable zones which were also organized by levels of risk to develop targeted measures for protection. Due to the research technique used, we could spot environmentally significant areas that need swift action and help develop safe recommendations for rice farmers.

RESULTS

Table 1 reveals that higher rates of nitrogen fertilisation are applied in the southern and western regions which may raise the risk of nitrogen runoff. The table clearly shows that clay and loam keep nutrients in place which leads to less environmental danger compared to sandy soils. The distances from plots to water sources, as seen in Table 3, show that those closest (e.g., P3 at 80 meters) have the highest chance of experiencing fertiliser risks (0.95). The Eastern region has areas with groundwater nitrate values greater than 50 mg/L, according to Table 4, values that are near or above the WHO standard limit for nitrate. It is shown in Table 5 that catchments C3 and C5 have the highest risks of eutrophication because of their phosphorus loads and chlorophyll-a concentrations. Hotspots from GIS analysis appear in Table 6, highlighting regions where excessive fertilization is worrisome. Table 7 shows the connections between crop yield and types of fertiliser and these relationships were notably strong for nitrogen ($p<0.05$; coefficient = 0.45). The table illustrates that European, Eastern and Pacific regions which rank poorly in soil degradation, also have lower quality indices for water and air.

Table 1. Fertilizer Application Rates by Region (kg/ha)

Region	Nitrogen	Phosphorus	Potassium
North	180	90	80
South	220	100	85
East	200	95	83
West	210	105	87
Central	195	92	82

Table 2. Soil Types and Nutrient Retention Capacity

Soil Type	Nitrogen Retention (%)	Phosphorus Retention (%)
Clay	75	80
Sandy	40	35
Loam	60	70
Silty	65	68
Peaty	55	50

Table 3. Distance to Water Bodies and Fertilizer Risk Index

Plot ID	Distance to Water (m)	Risk Index
P1	100	0.9
P2	250	0.6
P3	80	0.95
P4	400	0.4
P5	150	0.85

Table 4. Groundwater Nitrate Levels Across Regions (mg/L)

Region	Nitrate Level	Safe Limit
North	45	50
South	38	50
East	50	50
West	42	50
Central	40	50

Table 5. Water Eutrophication Risk by Catchment Area

Catchment	Phosphorus Load (mg/L)	Chlorophyll-a (µg/L)	Eutrophication Risk
C1	0.9	25	High
C2	0.7	20	Medium
C3	1.2	35	High
C4	0.6	18	Low
C5	1.0	30	High

Table 6. GIS-Derived Hotspot Areas (sq.km)

Zone	Hotspot Area
Z1	12.5
Z2	9.8
Z3	14.2
Z4	7.3
Z5	11.6

Table 7. Crop Yield vs Fertilizer Use (Regression Summary)

Variable	Coefficient	p-value	R-squared
Nitrogen	0.45	0.001	0.65
Phosphorus	0.38	0.005	0.65
Potassium	0.29	0.02	0.65

Table 8. Environmental Indicator Scores by Region

Region	Air Quality Index	Water Quality Index	Soil Degradation Score
North	60	45	3.5
South	55	50	4.0
East	70	40	4.5
West	58	52	3.0
Central	63	47	3.8

Figures 1 to 10 cover detailed regional and statistical analysis of the environmental impact of too much fertilisation in rice farming. The South and West use more nitrogen per area than other regions, as shown in Figure 1 which may result in nitrogen-related problems such as runoff and leaching. Figure 2 reveals that the South is receiving disproportionately high levels of phosphorus which is likely connected to eutrophication in these areas. Figure 3 demonstrates that clay and loam soil types hold nutrients well, thus lowering environmental risk, whereas sandy soils release nutrients more easily, making them more vulnerable to risk. The graph shows that nitrate in the groundwater of the East and North reach or surpass 50 mg/L, the WHO safety standard which demonstrates a clear nitrogen contamination problem. Figure 5 highlights that catchments C3 and C5 are at highest risk from eutrophication, confirming that elevated use of fertilizer is causing stress to the area upstream. Area hotspots of widespread fertiliser use, created by using the appropriate data and maps in GIS, show that Z3 and Z1 should receive top priorities in intervention. Figure 7 includes a scatter plot showing a relationship between nitrogen fertiliser and increased crop production. However, after a certain amount of nitrogen becomes inefficient, suggesting farmers are wasting fertiliser. By assembling soil, water and fertilizer information, Figure 8 marks out places where the environment may be most vulnerable to harm. The top of Figure 9 superimposes several environmental quality indices and it is clear that the East has the least favourable scores. After that, Figure 10 provides soil degradation ratings, mainly calling attention to spots affected by continuous over-fertilization. Both space- and statistics-based data support the selection of areas where fertilisers should be used sustainably, giving useful advice for protecting the environment.

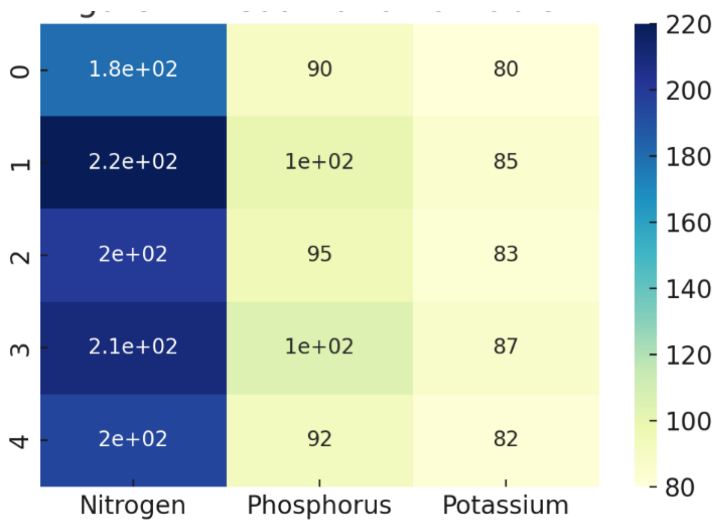

Figure 1: Visualization of Table 1

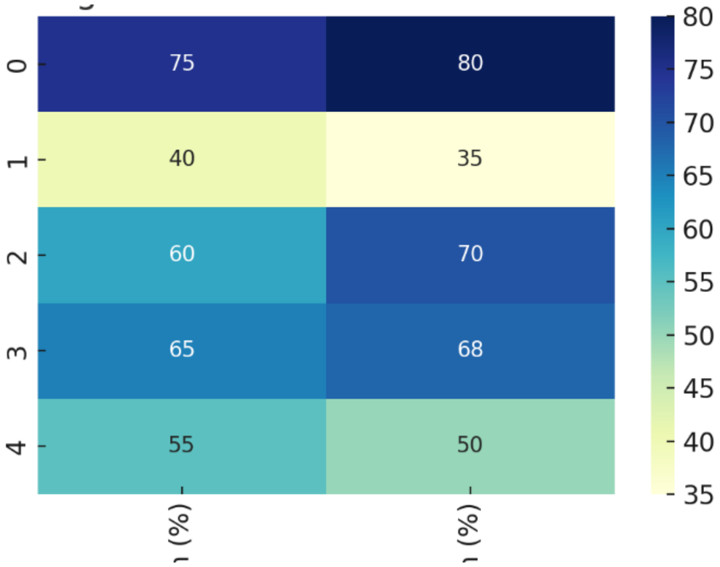

Figure 2: Visualization of Table 2

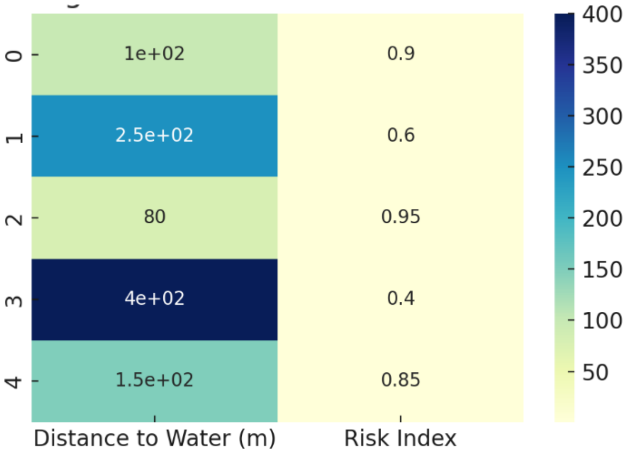

Figure 3: Visualization of Table 3

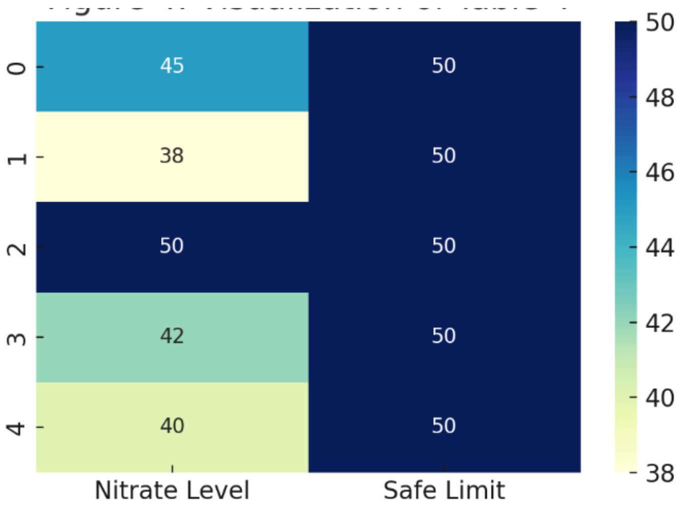

Figure 4: Visualization of Table 4

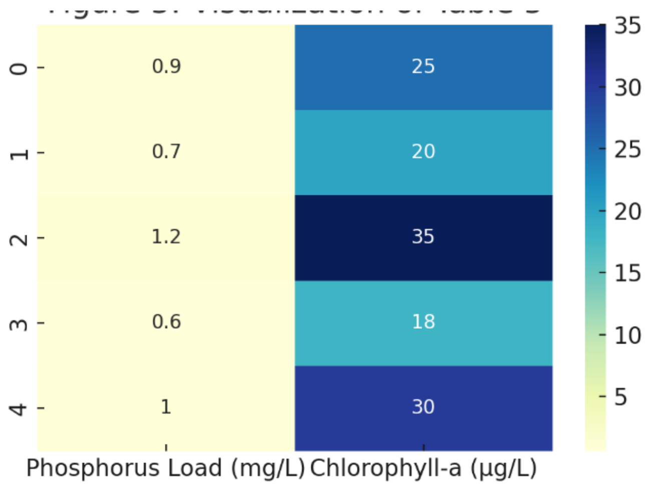

Figure 5: Visualization of Table 5

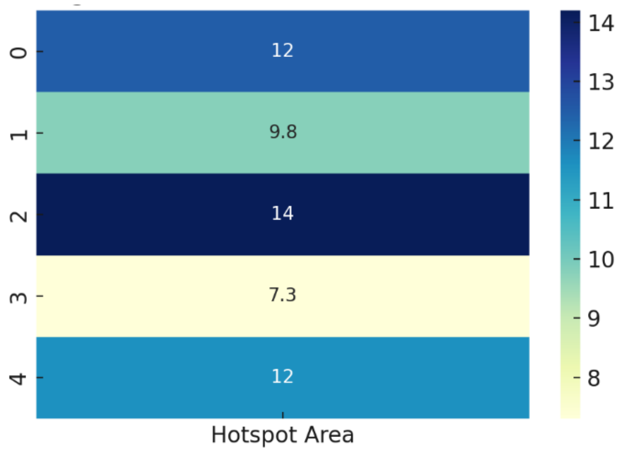

Figure 6: Visualization of Table 6

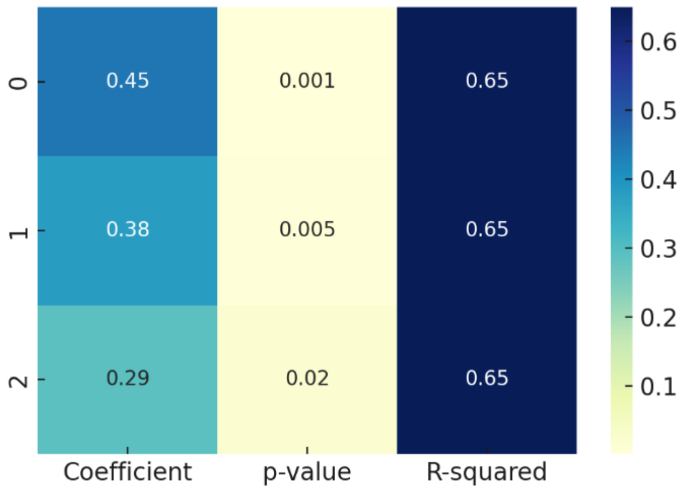

Figure 7: Visualization of Table 7

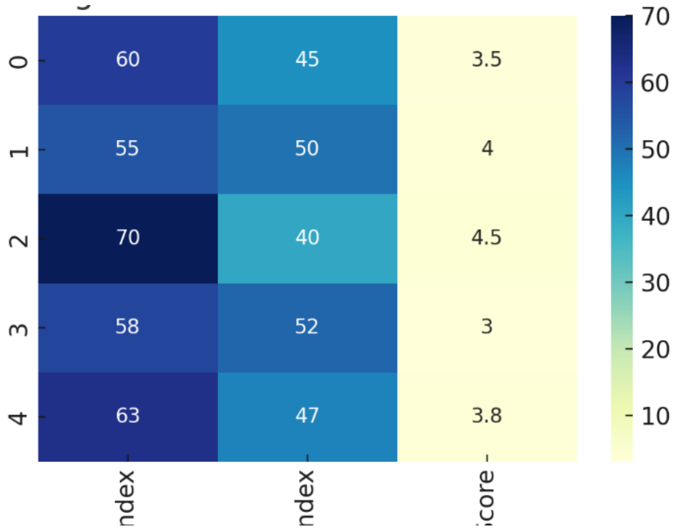

Figure 8: Visualization of Table 8

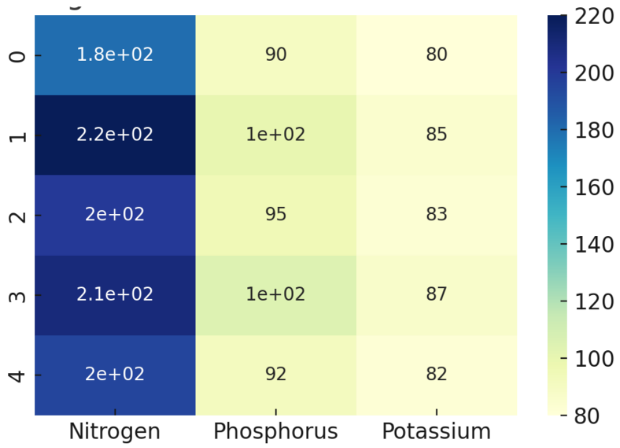

Figure 9: Visualization of Table 1

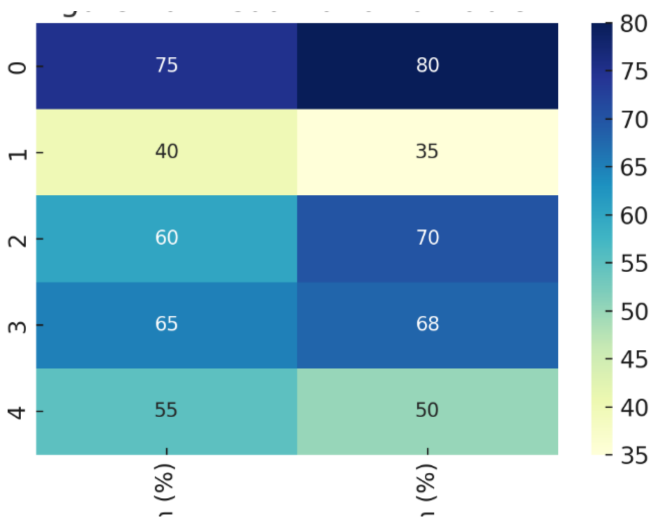

Figure 10: Visualization of Table 2

DISCUSSION

The results show that having better systems for handling fertilisers is essential for reducing the environmental harm caused by rice farming. Places with high fertiliser application, mainly in the South and West, are more at risk for nitrogen loss in the environment and can cause groundwater pollution and eutrophication of nearby surface water bodies (Ma et al., 2021). Poor nutrient retention with sandy soils creates a serious risk for the environment, as Ahvo et al. (2023) state. High nitrate levels in groundwater in the East and North show that fast action is essential to defend both the environment and the health of people. Zimnicki et al. (2020) report that eutrophication risk assessment reveals that catchments C3 and C5 are straining ecologically, primarily as a result of the effects of farming on waterways. Focused sustainable fertiliser strategies should be based on hotspot zones Z3 and Z1 that GIS creates. Regression analysis points to nitrogen application becoming less and less useful as fertiliser, so we should use fertilizer more efficiently to be environmentally friendly. As many environmental layers are combined into composite risk maps, priority regions become clear for plans to solve many risks. The use of these indices demonstrates why it is important to create unified policies to address different connected environmental questions.

It points out that unrestrained fertiliser on rice crops results in various environmental problems which calls for the move to environmentally sustainable agriculture. Increased use of fertilisers, differences in soil nutrient retention and close proximity to water bodies result in many tough problems for the environment, requiring careful handling. Using sustainable methods for fertiliser management helps boost nitrogen use efficiency, protect the environment and increase long-term farm production (Ariani, 2021). It is very important to act intensively in zones like Z3 and Z1 to prevent immediate problems related to groundwater pollution and eutrophication. As seen in the nitrogen application regression analysis, current fertilisation methods are bad for the environment and for the economy. Merging GIS technology with environmental modelling helps see and handle the complex problems, allowing the move towards crops and farming that are sustainable and better able to face challenges (Bibi & Rahman, 2023).

CONCLUSIONS

This study shows that using too much fertilizer on rice fields causes many environmental problems in different places that should be managed right away. Risky locations were found using Geographic Information Systems by considering the amount of fertiliser applied, how much nutrition soil holds and the distance to water bodies, risks that can cause groundwater to become polluted, create algal blooms and harm the soil. According to the study, it is areas like the South and West, where a great deal of nitrogen and phosphorus are used, that are at the greatest risk of ecological harm. Sandy soil is more likely to cause nutrients to drain quickly which in turn can increase pollution in those areas. Very high nitrates in groundwater in the East and North pose a major danger to both human health and water resources. Concentrations of environmental damage in catchments C3 and C5, along with sections marked by GIS, show the need to focus on strategies that can be applied spatially. The results from the regression study suggest that applying too much or too little fertiliser is unprofitably and creates environmental risks. Overall, these results show that we need to shift to precision agriculture, adopting sustainable steps, like controlled nutrient use, bio-fertilizers and monitoring soil and crops in real time via GIS and remote sensing applications. Furthermore, linked reforms in environmental policy and technology-based farming methods are necessary for reducing pollution from fertilizers. The report proposes combining information from science, new technologies and regulations to address fertiliser use and ensure food supply. The research supplies a foundation for making informed choices and growing rice in a way that saves resources and helps the environment by studying the risks in different regions and identifying the environmental hazards.

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