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Understanding Lowland Rice Farmers' Knowledge of Soil Fertilization Practices and Perceptions of Nitrogen-Induced Water Pollution Risks in the Ouémé Watershed, Central Benin

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Abstract: In Benin's lowland rice fields, water resources are vulnerable to nitrogen pollution due to shallow water tables, nutrient runoff, and inappropriate fertilization practices. This study assessed rice farmers' soil fertilization practices and their perceptions of water pollution risks. Data from 176 farmers were analyzed using descriptive statistics, logit, and tree regression. The results revealed that farmers applied an average of 79.4 ± 1.55 kg N ha^{-1} (53 kg N ha^{-1} from urea (46% N) and 26.4 kg N ha^{-1} from NPK), exceeding the recommended rate of 60 kg N ha^{-1}. This excess was due to the overapplication of urea by 75% of farmers, who applied it at an average rate of 115.2 ± 2.59 kg ha^{-1} instead of the recommended 75 kg ha^{-1}. Only 16% adopted pro-environmental practices. Farmers trained in water pollution risks and familiar with fertilizer policies were 36 times more likely to adopt sustainable practices. Downstream farmers applied less urea and were eight times more likely to adopt such practices. Farmers with over 10 years of experience were 17 times more likely to understand the watershed network. Despite 60.8% reporting eutrophication and 72.2% noticing water quality decline, only 34.1% linked nitrogen use and water pollution. Tree regression analysis indicated that 78% of untrained farmers were unaware of the environmental impacts of poor fertilization. These findings underscore the need to integrate specific concepts on nutrient management and water resource pollution into training programs and policies for lowland rice farmers in Benin, while also improving the knowledge transfer mechanism.

Keywords: rice farmers; lowlands; soil fertilization; water pollution; nitrogen; Benin

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Academic Editors: Catherine N. Mulligan and Antonio Panico

Received: 9 January 2025
Revised: 25 February 2025
Accepted: 5 March 2025
Published: 7 March 2025

Citation: Gbedourorou, S.K.; Tovihoudji, P.G.; Alonso, A.; Akponikpè, P.B.I.; Vanclooster, M. Understanding Lowland Rice Farmers' Knowledge of Soil Fertilization Practices and Perceptions of Nitrogen-Induced Water Pollution Risks in the Ouémé Watershed, Central Benin. *Water* **2025**, *17*, 779. https://doi.org/10.3390/w17060779

1. Introduction

Rice is a staple crop essential for global food security and national economic development [1,2]. It is typically grown in areas with high water potential, such as lowlands, wetlands, and environments where soils have a good water retention capacity [3,4]. These areas generally have shallow water tables and are often located near rivers. In recent years, rice production has increased in the lowland areas of Sub-Saharan Africa (SSA), due to the growing number of farmers and the degradation of upland areas caused by extreme weather events [5,6]. Despite this growing interest, rice consumption in SSA continues to exceed production, with grain yields (2.1 t ha^{-1} in 2021) falling short of expectations (4.6 t ha^{-1} in 2021) [7]. To meet rising demand, significant increases in rice production are needed [8,9]. This necessity has led to intensified rice production in the lowlands, inducing both greater use and poor management of mineral fertilizers [10,11]. Among these fertilizers, nitrogen is particularly important for plant growth and achieving higher yields [12,13]. However, poor nitrogen fertilizer management, coupled with the effects of climate change, have led to serious degradation of natural resources [14]. Nutrient imbalances resulting from agricultural practices have negatively impacted both aquatic and terrestrial ecosystems [15]. In the lowland areas of SSA, water pollution from residual fertilizers is a major concern [11,16]. Soil nutrient depletion is particularly severe in Africa, with net losses estimated at 10 kg N ha^{-1} and 4 kg P_2O_5 ha^{-1} [17]. This problem is exacerbated by the high vulnerability of groundwater in SSA watersheds to pollution [18].

In Benin, the lowlands, once considered marginal areas, are now under significant pressure for rice production [19,20]. According to FAO data, the area of rice cultivation in Benin grew from 28,787 ha in 2002 to 126,748 ha in 2021 [7]. This expansion is driven by the need to ensure the food security of a rapidly growing population and the high nutrient and water potential of the lowlands [17,21]. The rice cultivation of Benin is predominantly rainfed and monocultural, with low yields averaging only 2–3 t ha^{-1} [19,22]. Despite the increased cultivation areas, the demand for rice still exceeds the local supply, leading to high imports of 875,962 tons in 2020 [7,19]. To achieve higher yields, rice farmers use various amounts and types of nitrogen fertilizers [17,19]. However, the recommended fertilizer rates for lowland rice in Benin are 200 kg ha^{-1} for NPK (14-18-18) and 75 kg ha^{-1} for urea (46% N), equivalent to 60 kg N ha^{-1}, applied in 2–3 splits at planting, early tillering, and panicle initiation [17,23]. In Benin, the available NPK formulations are primarily produced for industrial crops such as cotton, and, to a lesser extent, maize. As a result, the recommended nitrogen doses for rice from NPK are typically adjusted based on the available NPK fertilizer. Some studies indicate that actual application rates are lower than these recommendations due to farmers' limited financial resources [17,24], while others suggest that the quantities applied often exceed the recommended levels [25]. Even at lower application rates, nitrogen losses can occur depending on soil moisture, the nature of the fertilizer source, the timing of application, and water flow dynamics. In both cases, the untimely application of nitrogen fertilizers further reduces their effectiveness, thereby increasing the risk of water pollution [26]. Moreover, the nitrogen use efficiency of rice is low, meaning that a significant portion of the nitrogen applied to fields is not absorbed by the crop [22]. This leads to severe environmental impacts, such as river eutrophication and soil pollution [27,28]. It is essential to supply plants with the optimum level of nutrients at the appropriate times, taking account of the initial soil nutrient content and adopting environmentally friendly fertilization practices [29]. Effective management of fertilizer use requires that farmers understand the agricultural environment and recognize its constraints.

The adoption of practices to enhance nitrogen use efficiency and mitigate environmental pollution remains limited [30,31]. Despite the development of various practices to reduce the impact of nitrogen fertilizers on water pollution, relatively little is known about how farmers make decisions regarding their application [31,32]. Farmers often hold negative attitudes towards the perceived environmental benefits of good practices and compliance measures [33]. Promoting effective nutrient management presents significant technical and social challenges [34]. Therefore, several approaches have been developed to study farmers' attitude towards the use of agricultural practices including nutrient management [35,36]. These approaches aim to identify the factors influencing the adoption of agricultural technologies and human behavior, including personal, physical, economic, and institutional dimensions [36]. One of the most widely used frameworks in this context is Ajzen's Theory of Planned Behavior (TPB) [37,38], which extends the Theory of Reasoned Action [39]. The TPB posits that human decision making is influenced by three major components: an individual's evaluation of the behavior (attitude toward the behavior), perceived social pressure to perform or not perform the behavior (subjective norm), and perceived behavioral control (the individual's perceived ability to carry out the behavior) [37,40]. This framework has been extensively validated and is considered a structured yet flexible model for explaining farmers' decisions to adopt sustainable agricultural practices [41,42]. However, some researchers argue that the TPB does not fully capture all the factors influencing farmers' attitudes [43]. To enhance its predictive capacity, various conceptual frameworks have been developed based on the TPB [44]. Daxini et al. [41] introduced the predictor "perceived resources," defined as the extent to which a farmer believes they possess or have access to the necessary resources (e.g., finance, labor, and time) and technical infrastructure (e.g., information) to support them in adopting sustainable practices [45]. This predictor, along with subjective norms and perceived behavioral control, has been found to be positively correlated with farmers' intentions [41]. In addition to these psychological determinants, socio-economic factors have been identified as critical drivers of agricultural technology adoption [35,41]. The strength of an approach lies in its ability to integrate these various factors, providing a more comprehensive understanding of decision making. An integrative and interdisciplinary research approach, combinning both natural and social sciences, offers a more holistic perspective on the issue [46,47].

Over the past two decades, Dessart et al. [36] classified behavioral factors influencing the adoption of sustainable agricultural practices into three main categories. First, dispositional factors, which refer to internal and relatively stable characteristics of an individual. Second, social factors, which relate to farmers' interactions with others (e.g., fellow farmers, agricultural advisors) and include social norms. Third, cognitive factors, which involve learning and reasoning processes, including farmers' perceptions of the benefits, costs, and risks associated with a sustainable practice, as well as their confidence in their ability to adopt it [36,48]. Similarly, Michie et al. [49] developed the Behavior Change Wheel (BCW), based on the Capability, Opportunity, Motivation-Behavior (COM-B) model. This framework assumes that behavior can be influenced by changes in intentions, which are shaped by attitudes, perceptions, and both internal and external environments [50]. Some studies have highlighted the important role of knowledge transfer in decision making regarding the adoption of agricultural technologies [51]. This study builds on recent frameworks to incorporate psychological, sociological, economic, environmental, and knowledge-based factors in understanding farmers' adoption of good nitrogen management practices and their perceptions of water pollution issues in lowland rice farming areas of Benin.

Numerous studies conducted in developed countries have examined how farmers make decisions regarding the adoption of nutrient management strategies (such as nitrogen fertilizers) and the factors influencing these choices [52,53]. Several recurring factors have been identified, including farm size [54], education level [55], source of information [53,56], type of farming and crops grown [57], agricultural management practices [58], income level, and farmers' environmental attitudes. Furthermore, farmers' perceptions of water pollution caused by agricultural nitrogen play a key role in decision making [59]. These perceptions are influenced by various factors, such as their awareness of environmental issues [60] and their understanding of how their practices affect water quality [61]. Some farmers do not adopt eco-friendly practices due to a lack of information [34,62], a low perception of risks, and a limited understanding of the benefits of sustainable agricultural practices [61,62]. While many studies indicate that farmers acknowledge the existence of water quality issues, they only partially attribute these problems to agricultural practices [35,52]. However, in Scotland's Nitrate Vulnerable Zone, most farmers are aware that excessive fertilizer and manure application, as well as poor timing of applications, contribute to water pollution. Despite this awareness, many are reluctant to admit that agriculture is directly responsible for these issues [33,46].

Most studies generalize their findings to all farmers without considering environmental and regional specificities [63]. Although farm characteristics and access to information are identified as key factors influencing farmers' decision making, there is a clear gap in the literature regarding the determinants of adoption and perception in specific ecosystems (such as sloped lands, erodible areas, lowlands, and wetlands) and for certain types of farming (e.g., rice fields, livestock) [54]. Moreover, these studies have mainly been conducted in developed countries, whereas the factors influencing the adoption of agricultural practices can vary depending on the economic and social context. For instance, studies suggest that farm size positively influences the adoption of sustainable practices, assuming that larger farms have the financial resources to invest in innovation [35,64]. However, this relationship is not systematic in developing countries, where some farmers cultivate large inherited lands without necessarily having the financial and logistical means to adopt new agricultural practices. Therefore, it is crucial to study these factors while considering the specificities of ecosystems and regional contexts [34,35].

In Sub-Saharan Africa, few studies have analyzed farmers' perception of the link between soil fertilization and water pollution. Yet, in lowland areas, farmers are aware of environmental degradation [12]. In Benin, research on rice cultivation has mainly focused on farming and fertilization practices without examining farmers' perception of water pollution risks [19,20,65]. This study stands out due to its specific approach: it analyzes nitrogen use in a hydrologically and pedologically complex ecosystem such as lowland, while exploring rice farmers' perceptions of nitrogen water pollution in Benin, a developing country in Sub-Saharan Africa. The objective is not only to identify the factors influencing these perceptions but also to assess the extent of their influence on the adoption of sustainable agricultural practices.

This study aims to assess farmers' fertilization practices in the lowland rice fields of central Benin and explore their perceptions of nitrogen-induced water pollution risks. The specific objectives are to (i) understand rice fertilization practices in central Benin, (ii) identify factors influencing the adoption of pro-environmental practices, (iii) determine factors contributing to farmers' understanding of the watercourse system within the watershed area, and (iv) examine rice farmers' perceptions of nitrogen pollution risks and the factors influencing awareness of their consequences. The findings from this study will offer valuable insights into the barriers to adopting environmentally friendly fertilization practices and support the development of decision-making tools to mitigate water pollution risks.

2. Materials and Methods

2.1. Study Area

The study was conducted in two sub-basins of the Ouémé watershed in Benin: Sowé in the Zou sub-basin (located between 2°13′7″ to 2°18′7″ E and 7°49′3″ to 7°59′ N) and Kossi in the Upper Ouémé sub-basin (located between 2°9′7″ to 2°13′33″ E and 7°57′46″ to 8°2′38″ N) (Figure 1). These sub-basins cover an area of 141.90 km^2 within the agroecological zone ZAE-5 in Benin. This region is situated in a climatic transition zone between the Guinean climate to the south and the sub-equatorial climate to the north. This transitional climate results in highly unpredictable rainfall patterns, with occasional droughts even during the rainy season [66,67]. The annual average rainfall ranges between 900 mm and 1200 mm, but recent climate variations have disrupted the regularity of the seasons [68]. The highest mean number of rainy days is observed for light rainfall (<10 mm per day), while the lowest occurs for extreme rainfall (>50 mm per day) [69]. The bimodal rainfall pattern is gradually disappearing, with rains starting later and droughts occurring intermittently within the rainy season [70]. The average temperature is around 28 °C, with minimum and maximum averages of 21.2 °C and 32.5 °C, respectively [71,72]. The annual average relative humidity is 60%, ranging from a minimum average of 21.1% to a maximum average of 87.1% [72]. The dominant upland soil types are ferruginous soils, which have favorable properties for cultivation, but hydromorphic soils are encountered in the lowlands [67]. While ferruginous soils support the cultivation of major crops such as rice, soybeans, corn, and yams, mostly rice and vegetables are often practiced on hydromorphic soils. The selection of these two sub-basins was significant because they are key areas for rice production in Benin. The Sowé sub-basin hosts experimental rice cultivation sites managed by the "Institut National des Recherches Agronomiques du Bénin" (INRAB) and the "Conseil de Concertation des Riziculteurs du Bénin" (CCR-B). In this study area, rice cultivation is primarily rainfed. The rainy season begins in May, with a coefficient of variation of 29%, and ends in November [69,73]. In general, rice cultivation starts in early June and ends in late December [22]. The main rice varieties grown in the area include NERICA (NERICA 1, NERICA 2, NERICA 4, and NERICA 5), WAB 32, and IR841. These varieties are cultivated on plots that are usually plowed manually or with a cattle-drawn plow [22,74].

2.2. Demographic Characteristics of Region

The study region covers a surface of 1350 km^2, with a population density of approximately 51 inhabitants per km^2 [75]. Agriculture is the primary source of income for the population. It serves as the main livelihood for 85% of the residents [76]. The main crops grown are cereals, particularly maize, rice, and sorghum, followed by root and tuber crops as well as legumes. The region is well suited to rice cultivation due to the presence of significant water bodies, including the Ouémé River, and eroded lowlands. It is one of the largest rice-producing areas in Benin. In recent years, rice has become one of the most consumed cereals in the country, with an average annual consumption per capita estimated at 25 to 30 kg [77]. The trade of rice and other staple crops is primarily local. However, due to the region's favorable geographical position, which facilitates trade between Nigeria, Benin, and Togo, a portion of the rice is informally exported to neighboring countries in the sub-region [77].

2.3. Methodology, Sampling, and Data Collection

Mixed methods research is widely used to assess farmers' attitudes toward agricultural technology [78]. This approach collects and analyzes both quantitative and qualitative data within the same study to provide a comprehensive understanding of response variables [79,80]. Qualitative methods allow for the exploration of a broader range of variables related to the research questions, while quantitative methods provide measurable data that can be generalized to larger populations [46]. The combination of these methods enhances the research process by leveraging their respective strengths [81].

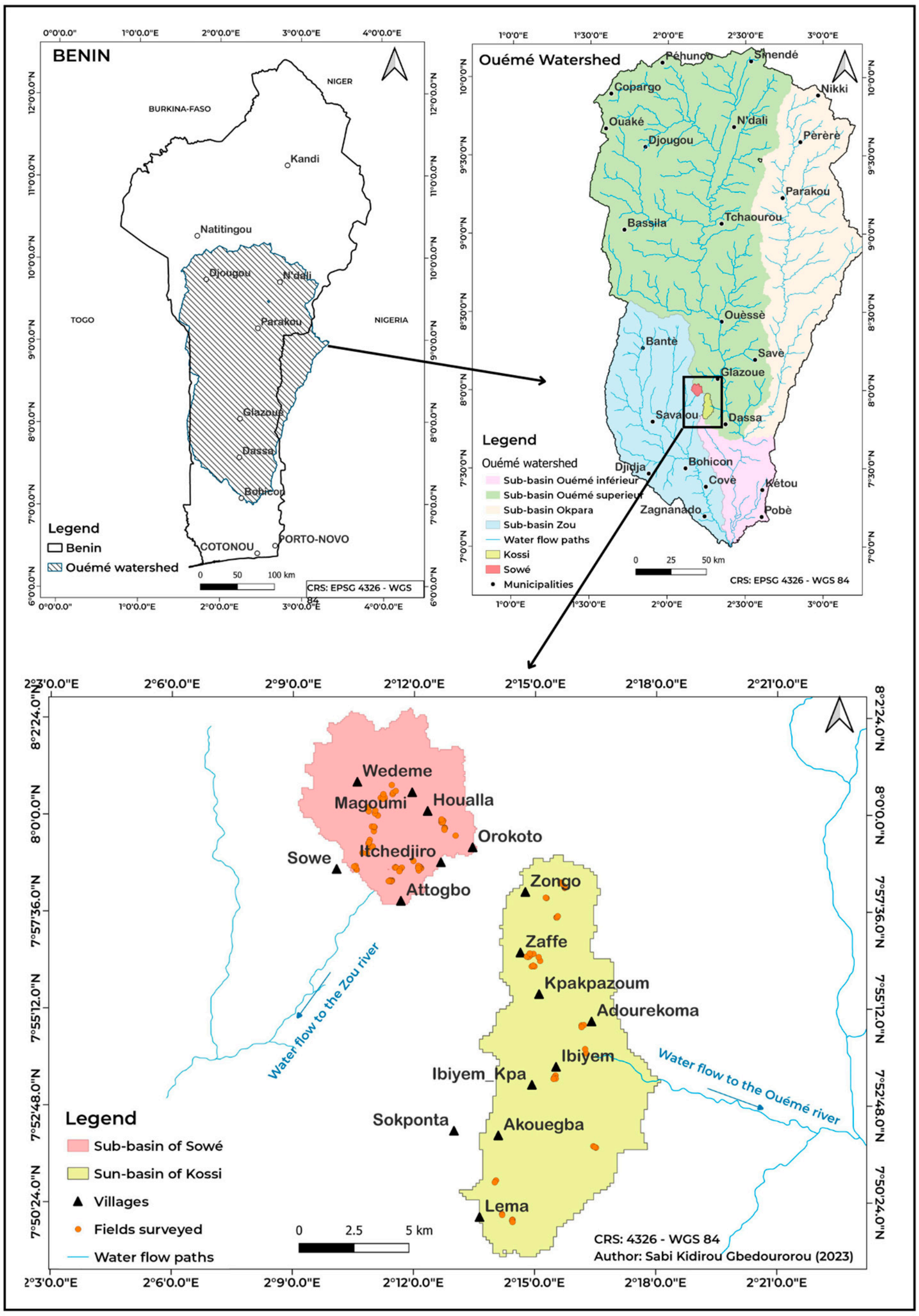

Figure 1. Map of study area.

Several studies have employed survey-based approaches using semi-structured questionnaires to collect both qualitative and quantitative data [33,35]. These surveys have been conducted through various means, including telephone interviews [33], mail surveys, and in-person interviews with farmers [31]. Additionally, focus group discussions with farmers have been used to explore their cultivation practices, water and nutrient management strategies, challenges, concerns, and potential solutions or mitigation strategies [20,82]. Field surveys, often combined with semi-structured interviews, have also been used to evaluate decision-making processes and their impact on agricultural system outcomes [16,25]. Furthermore, descriptive studies using questionnaires help to define the opinions, attitudes, and behaviors of target populations on specific topics.

In this study, a survey method was used through in-person interviews. Interviewers engaged farmers at convenient times, such as during breaks from fieldwork or at home.

Questionnaires were translated into the local language to facilitate discussions and exchanges with farmers. Detailed maps of the watershed and lowland areas were created for each lowland, highlighting features such as upstream and downstream distinctions and watercourse characteristics. In lowland areas, the terms upstream and downstream refer to the relative position of a given zone within a hydrological network. Upstream corresponds to the head of the ecosystem, located at the beginning of the network. It receives water from rainfall-fed streams or small tributaries and carries sediments. Downstream refers to areas further along the network that receive water from upstream zones and closer to the outlet [83]. Surveyors carried physical copies of these maps during household interviews, enabling farmers to accurately locate their fields. For interviews conducted in the fields, the geographical coordinates of the fields were automatically recorded using a mobile application, ensuring precise spatial data collection (Figure 1).

The sample size was determined using the normal approximation of the binomial distribution (Equation (1)) [84].

$$n = \frac{U^2_{1-\alpha/2} \cdot p(1-p)}{d^2} \quad (1)$$

where n represents the sample size, $U^2_{1-\alpha/2}$ = 1.96 is the quantile for a 95% confidence level, p = 0.17 is the proportion of rice farmers, and d is the margin of error.

The margin of error d was set at 0.04. Villages were selected based on the number of rice farmers and the importance of rice production in the sub-basins. Rice farmers were chosen randomly from these villages, ensuring their fields were located within the target sub-basin. This selection process was carried out in collaboration with the "Agence Terriotoriale de Développement Agricole (ATDA)". In total, 176 rice farmers were surveyed across 16 villages and 27 lowland areas within the two sub-basins.

Surveys were conducted from November to December 2022. Personal interviews were carried out using a semi-structured questionnaire that covered various topics, including farmer demographics, soil fertilization practices, knowledge of watershed systems, and perceptions of water pollution. These interviews were held in the local language and responses were recorded using the KoboCollect application. Interviews took place both in farmers' fields and within local communities.

2.4. Selection of Dependent and Explanatory Variables

For this study, four response variables were defined as follows: (a) the quantity of urea (46% N) fertilizer applied; (b) the adoption of pro-environmental fertilization practices; (c) knowledge of the watercourse system in the watershed; and (d) an awareness of water pollution risks focusing on the recognition of potential risks related to nitrogen-induced eutrophication. Additionally, a comprehensive analysis was conducted to understand rice farmers' perceptions of water pollution risks associated with nitrogen and their strategies for mitigating these risks.

Explanatory variables were selected based on a detailed review of previous research [35,82,85–87], which highlighted the connections between fertilization practices and farmers' perceptions of water pollution risks. These variables were categorized into four groups: socio-demographic characteristics, field characteristics, soil fertilization practices, and farmers' perceptions of nitrogen-related water pollution (Table 1). In addition to these main variables, other specific factors were included and clarified through targeted questions. For example, information was gathered on whether farmers had undertaken land management practices, such as building small dikes, sluices, and erosion control measures. The practice of splitting urea application was also investigated to determine if fertilizer was applied in a single or multiple application during the growing season, as this can impact both environmental effects and crop yield. The criteria for choosing fertilizer doses were examined to understand whether farmers relied on personal judgment, agronomic recommendations, or guidelines from agricultural agencies. Pro-environmental fertilization practices were analyzed to determine if environmental concerns influenced farmers when choosing fertilizer doses and application methods. A specific interest was in whether practices were adjusted to protect the environment, such as by reducing fertilizer doses or changing application techniques to prevent pollution. Finally, farmers' knowledge of the hydrographic network was explored to understand how water and nutrients move on and off the farm. This understanding can aid in adopting sustainable practices, avoiding misuse of agricultural inputs in sensitive areas, and ultimately reducing environmental impact.

Table 1. Description of the variables.

Variables	**Description**	**Expected Sign for Dependent Variable**		
		(b)	**(c)**	**(d)**
Dependent Variables	Statistical Analysis/Model Type			
Dose of urea fertilizer (a) Pro-environmental practices (b)	Chi-squared test of independence Logit regression (Model1) and tree regression			
Knowledge watershed network (c)	Logit regression (Model 2)			
Perceived water pollution (d)	Logit regression (Model 3)			
Explanatory Variables	Categories			
Socio-demographic factors				
Gender	Farmer's gender (0 = female, 1 = male)	+/-	+	+/-
Age	Farmer's age (0 = "18–35", 1 = "36–45", 2 = ">45") in years	+/-	+	+/-
Education	Education level of farmers (0 = unschooled, 1 = schooled)	+	+/-	+
Farming experience	Experience in the use of lowland areas (0 = "<10», 1 = "10–19", 2 = ">19") in years	+	+	+
Membership of farm organization	Member of rice-growers association (0 = no, 1 = yes)	+/-	na [1]	na
Training on water pollution	Trained on water pollution (0 = no, 1 = yes)	+	+/-	+
Training on rice cultivation	Trained on rice cultivation (0 = no, 1 = yes)	+	na	na
Spatial factors				
Farm location	Field location in the lowland (0 = upstream, 1 = middle, 2 = downstream)	+	+/-	+
Farm size	Size of the field (0 = "<1", 1 = "≥1") in ha	+/-	na	na
Developed lowlands	Developed field (0 = no, 1 = yes)	+	na	na
Fertilization factors				
Urea dose	Dose of urea (0 = "50–75", 1 = "76–100", 2 = ">101") in kg/ha	+	na	+
Split fertilizer application	Splitting urea application (0 = no split, 1 = split)	+	na	na
Method of fertilizer application	Method of applying fertilizer (0 = broadcast, 1 = in-hole)	+	na	na
Choice criteria	Choice criteria of fertilizer and dose (0 = recommended, 1 = fertilizer available on the market, 3 = field history, 4= arbitrary)	+	na	na
Total fertilizer used by crop	Consideration of total use by the crop of total applied fertilizer (0 = no, 1 = yes)	+/-	na	na
Crop rotation	Practice of crop rotation (0 = no, 1 = yes)	-	na	na
Knowledge of fertilizer use policies	Knowledge of fertilizer use regulations (0 = no, 1 = yes)	-	na	na
Pro-environmental fertilization practices	Adoption of pro-environmental practices (0 = no, 1 = yes)			+

Table 1. *Cont.*

Variables	Description	Expected Sign for Dependent Variable		
		(b)	(c)	(d)
Knowledge factors of hydrographic network				
Knowledge of water leaving the field	Knowledge about fate of water that leaves the farm (0 = no, 1 = yes)	na	+/-	na
Knowledge of final outlet	Knowledge about the outlet of the watershed (0 = no, 1 = yes)	na	+	na
Knowledge of the process of nutrient runoff from upstream to downstream	Knowledge about the fertilizer's fate in terms of the position of the field in the toposequence (0 = no, 1 = yes)	+/-	+	na
Knowledge of watershed network	Knowledge about the hydrographic network of the watershed (0 = no, 1 = yes)	na		+/-
Perception factors				
Have perceived water organoleptic degradation	Observed degradation of the organoleptic quality of the water (smell, taste, color) (0 = no, 1 = yes)	na	na	+
Knowledge of how poor fertilizer affects water	Awareness about the link between poor fertilization practices and water pollution by nitrate (0 = no, 1 = yes)	+	na	+
Knowledge of water pollution factors	Awareness of other factors that contribute to water pollution (0 = no, 1 = yes)	na	na	+/-
Water pollution observed	Observed eutrophication (0 = no, 1 = yes)	na	na	

Note: [1] 'na' = the variable is not included in the model.

2.5. Data Analysis

Survey data were analyzed using descriptive and multivariate statistics. The socio-demographic characteristics of farmers, field characteristics, fertilization practices, and knowledge of water pollution factors were examined with descriptive statistics and chi-squared tests of independence. For farmers' knowledge of water pollution, descriptive analysis was supplemented with tree regression (Table 2).

Table 2. Summary of statistical analysis.

Response Variables	Statistical Analysis/Model Type	Statistical Index
Soil fertilization practices	Descriptive analysis Chi-squared test of independence	Proportion *p*-value
Farmers perception and attitude on water pollution by nitrogen	Descriptive analysis	Proportion
Pro-environmental practices	Logistic regression (Model 1)	Goodness of fit; OR and *p*-value Tree decision
	Tree regression	Tree decision
Knowledge of watershed network	Logistic regression (Model 2)	Goodness of fit; OR and *p*-value
Observed water pollution (as eutrophication).	Logistic regression (Model 3)	Goodness of fit; OR and *p*-value

Logit regression models were applied to response variables, including adoption of pro-environmental fertilization practices (Model 1), knowledge of watershed networks (Model 2), and perceived water pollution (Model 3). These models incorporated a set of explanatory variables that are detailed in Table 1. Logistic regression estimates the relationship between a binary dependent variable and one or more explanatory variables [88]. Widely used in studies on perception, technology adoption, and climate change adaptation, it helps identify factors influencing perception and adoption stages [35,58,89–91]. The model quantifies the effects of explanatory variables (X) on the latent variable y* illustrating the influence of each explanatory variable on the probability of belonging to a specific category of the dependent variable (Y) compared to another category [92]. This probability is modeled using a sigmoid curve, constrained between 0 and 1 [91]. The logit transformation for multiple explanatory variables is expressed as Equation (2):

$$y^*_{ij} = \sum_{j=1}^{n} \beta_j X_{ij} + \varepsilon_{ij} \quad (2)$$

where y^*_{ij} represents the latent variable for the i farmer with respect to a particular response to the j explanatory variable; β_j is the coefficient for the j explanatory variable; X_{ij} is the value of the j explanatory variable for the i farmer; and ε_{ij} is the error term.

Since y^*_{ij} is not directly measurable, the dependent variable y_{ij} in binary logistic regression takes the value 0 or 1, using the following rule:

$$y_{ij} = \left\{1, \ \ if \ \ y^*_{ij} > 0; \ 0, \ \ otherwise\right\} \quad (3)$$

where y_{ij} is an observed variable indicating that the farmer i answers "Yes". Otherwise, the farmer answers "No" to the dependent variable.

In the logit model, the predicted probabilities are limited to between 0 and 1.

$$pr[y_{ij} = 1|x] = \frac{exp(\beta_j X_{ij})}{1 + exp(\beta_j X_{ij})} \quad (4)$$

where $pr[y_{ij} = 1|x]$, represents the probability of selecting an option for the response variable.

Interpreting the results of binary logit regression involves assessing the coefficients for their signs and significance [91,92]. However, evaluating coefficients alone does not provide a complete understanding of the relationship between the response and explanatory variables. A more effective approach is to examine the odds ratios (OR) rather than focusing solely on the coefficients [93].

The validity and performance of the logit models were assessed using overall significance and goodness of fit measures. Model accuracy was evaluated using the Receiver Operating Characteristic (ROC) curve and out-of-sample predictions [35,91,94]. The ROC curve plots the model's performance by graphing sensitivity (true positive rate) against 1-specificity (false positive rate) across various classification thresholds from 0 to 1. The Area Under the Curve (AUC) complements the ROC curve by quantifying the model's discriminatory power, with an AUC value approaching 1 indicating excellent performance and a strong ability to distinguish between classes.

3. Results

3.1. Characteristics of Rice Farmers and Rice System

The surveyed farmers had an average age of 43 years and an average of 13 years of farming experience, with 38.6% reporting less than 10 years of experience in rice farming (Table 3). Female farmers accounted for 47.2% of the lowland rice farmers in the study area. Additionally, 51.7% of the farmers had no formal education, and among those who had received some education 63.7% did not progress beyond the secondary level. Although 58.5% of the farmers had received training in rice cultivation, only 25.5% had been trained on issues related to water pollution (Table 3).

Table 3. Socio-demographic characteristics of rice farmers surveyed.

Variables	Characteristics	N (Proportion %)
Gender	Female	83 (47.2)
	Male	93 (52.8)
Age (in years)	18–35	53 (30.1)
	36–45	62 (35.3)
	>45	61 (34.6)
Farming experience (in years)	<10	67 (38.1)
	≥10	109 (61.9)
Education	Unschooled	91 (51.7)
	Basic school	55 (31.3)
	Secondary school	30 (17)
Training on technique of rice cultivation	No	73 (41.5)
	Yes	103 (58.5)
Training on water pollution issues	No	131 (74.5)
	Yes	45 (25.5)
Source of drinking water at field	River	37 (21)
	Well	11 (6.3)
	Drilling	128 (72.7)
Farm size (ha)	Continuous	(mean: 1.19 ± 0.7)
Location	Upstream	49 (27.8)
	Middle	60 (34.1)
	Downstream	67 (38.1)
Crop rotation	No	117 (67.5)
	Yes	59 (33.5)
Main crops in rotation with rice	Cowpea	25 (39.7)
	Soybean	16 (25.4)
	Maize	13 (20.6)
	Vegetables	9 (14.3)

Regarding their sources of drinking water, 27.3% of the farmers relied on streams, rivers, and wells while working in the fields. The average field size cultivated was 1.19 hectares, distributed across the lowland toposequence; 27.8% of fields were located upstream, 34% in the middle, and 38% downstream (Table 3). The rice cropping system adopted by the surveyed farmers was predominantly rainfed lowland rice cultivation. Within these lowland areas, 33.5% of the farmers practiced crop rotation involving rice and other crops such as cowpea (39.7%), soybean (25.4%), maize (20.6%), and vegetables (14.3%) (Table 3).

3.2. Soil Fertilization Practices in Lowland Rainfed Rice Cropping

Fertilization was practiced by 97.2% of the surveyed rice farmers, with only five farmers reporting no fertilizer use on their fields. Among those who applied fertilizers, mineral fertilizers were the most commonly used, while organic fertilizers were utilized by only 16.7% of the farmers (Table 4). The mineral fertilizers included urea (46% N) and NPK (14:18:18), whereas organic fertilizers consisted of cattle and poultry manure. Farmers reported applying an average 115.2 ± 2.59 kg ha^{-1} (53 kg N ha^{-1}) for urea and

189 ± 2.6 kg ha^{-1} (26.4 kg N ha^{-1}) for NPK, resulting in a total nitrogen application of 79.4 ± 1.55 kg N ha^{-1} (Figure 2). Only 24% of the farmers followed the recommended fertilizer application rates for rice cultivation in Benin (Table 4). The majority (81.9%) of farmers used the broadcast method to apply mineral fertilizers, while 18.1% adopted deep placement methods. NPK was typically applied once during the tillering stage, and urea (46%N) was applied once during the panicle initiation stage. Additionally, 19% of farmers applied fertilizers while their plots were submerged (Table 4).

Table 4. Soil fertilization practices.

Variables	Characteristics	N (Proportion%)
Application of fertilizer	No	5 (2.8)
	Yes	171 (97.2)
Fertilizer type	Organic	6 (16.7)
	Mineral	171 (100)
Types of fertilizers (organic and mineral)	Urea (46%N)	171 (100)
	NPK	171 (100)
	Cattle manure	4 (2.3)
	Poultry manure	2 (1.2)
Method of fertilizer application	Broadcast	140 (81.9)
	Deep placement	31 (18.1)
Soil water status at the time of fertilizer application	Unsaturated	23 (10)
	Saturated	163 (70)
	Submerged	45 (19)
Choice criteria of fertilizer type and dose	Recommended	41 (24)
	Arbitrary	91 (53.2)
	Fertilizer available on market	19 (11.1)
	Field history	20 (11.7)

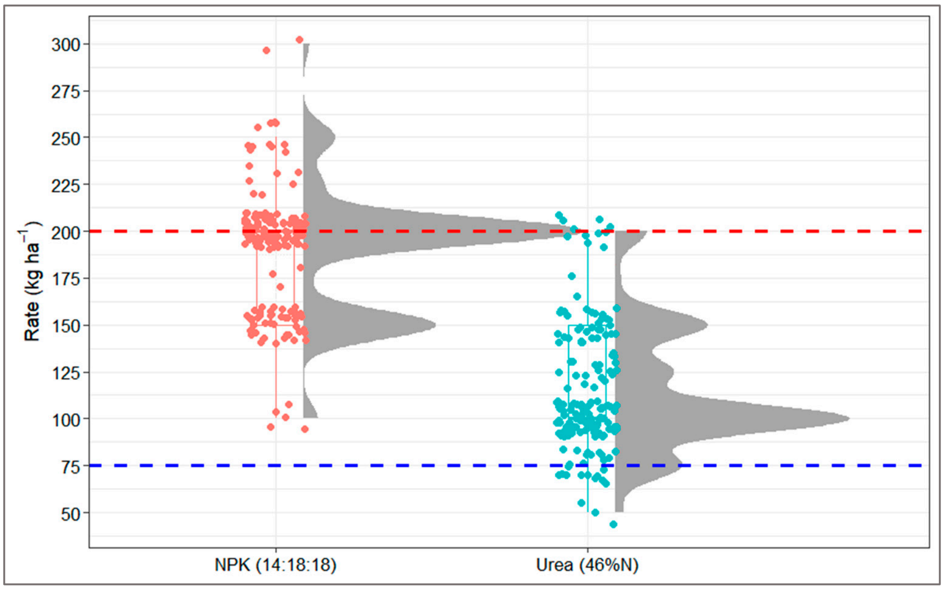

Figure 2. Dose of mineral fertilizers applied by the surveyed rice farmers. The red line represents the recommended dose for NPK in rice cultivation in Benin, and the blue line represents the recommended dose for urea application.

The findings of this study revealed that field location within the lowlands and the practice of crop rotations significantly influenced ($p < 0.05$) the quantity of urea (46% N) applied by rice farmers (Table 5). Notably, 62% of farmers who applied low doses of urea were situated downstream in the lowlands. In contrast, socio-demographic factors such as age, education level, gender, and training in rice cultivation did not have a significant effect ($p > 0.05$) on the urea application rate (Table 5).

Table 5. Determinants of urea fertilizer rates applied in the field.

Urea Dose (kg ha^{-1})	**50–75, N = 21** [1]	**76–100, N = 81** [1]	**>100, N = 64** [1]	**Overall, N = 171** [1]	***p*-Value** [2]
Age group					0.642
18–35	10 (38%)	25 (31%)	15 (23%)	50 (29%)	
36–45	7 (27%)	29 (36%)	24 (38%)	60 (35%)	
46+	9 (35%)	27 (33%)	25 (39%)	61 (36%)	
Education					0.678
Unschooled	13 (50%)	45 (56%)	31 (48%)	89 (52%)	
Schooled	13 (50%)	36 (44%)	33 (52%)	82 (48%)	
Farming experience class (year)					0.544
<10	8 (31%)	29 (36%)	27 (42%)	64 (37%)	
10–19	14 (54%)	34 (42%)	22 (34%)	70 (41%)	
20+	4 (15%)	18 (22%)	15 (23%)	37 (22%)	
Have received training on water pollution	10 (38%)	19 (23%)	13 (20%)	42 (25%)	0.184
Have received training on rice cultivation	15 (58%)	49 (60%)	37 (58%)	101 (59%)	0.937
Field location					0.007
Upstream	3 (12%)	19 (23%)	27 (42%)	49 (29%)	
Middle	7 (27%)	31 (38%)	19 (30%)	57 (33%)	
Downstream	16 (62%)	31 (38%)	18 (28%)	65 (38%)	
Farm size					0.353
<1 ha	9 (35%)	25 (31%)	14 (22%)	48 (28%)	
1 ha+	17 (65%)	56 (69%)	50 (78%)	123 (72%)	
Landscaped field	1 (3.8%)	9 (11%)	9 (14%)	19 (11%)	0.430
Choice criteria of fertilizer					0.094
Recommended	12 (46%)	20 (25%)	9 (14%)	41 (24%)	
Fertilizer available	2 (7.7%)	10 (12%)	7 (11%)	19 (11%)	
Field history	3 (12%)	9 (11%)	8 (12%)	20 (12%)	
Arbitrary	9 (35%)	42 (52%)	40 (62%)	91 (53%)	
Crop rotation	19 (73%)	39 (48%)	25 (39%)	83 (49%)	0.014
Knowledge of fertilizer use regulations	10 (38%)	20 (25%)	16 (25%)	46 (27%)	0.352
Adoption of pro-environmental practices	19 (73%)	37 (46%)	17 (27%)	73 (43%)	<0.001

Notes: [1] n (% in parentheses); [2] Pearson's chi-squared tests: Fisher's exact test.

3.3. Factors Influencing the Adoption of Pro-Environmental Fertilization Practices in Lowland Rainfed Rice Cropping

The logit regression model (Model 1) for the adoption of pro-environmental fertilization practices by rice farmers demonstrated strong performance, with a chi-squared value of 130 (20 degrees of freedom) that was highly significant (p-value < 0.05). This result underscores the collective influence of the predictor variables. The model outperformed an intercept-only model, achieving a Nagelkerke R-squared value of 0.71 (Table 6). The model accuracy was 86.54%, and ROC analysis yielded an AUC of 94.3%, highlighting the model's power and discriminative ability (Figure 3).

Table 6. The logistic models' significance and goodness of fit.

Logit Model	Chi-Squared	Df	P-Level	Log Likelihood	AIC	Nagelkerke R-Squared	Model Correctness (%)
Model 1	130.01	20	<0.001	−51.69	149.39	0.71	86.54
Model 2	90.88	12	<0.001	−72.84	169.69	0.55	83.52
Model 3	39.43	15	<0.001	−98.14	228.28	0.27	73.29

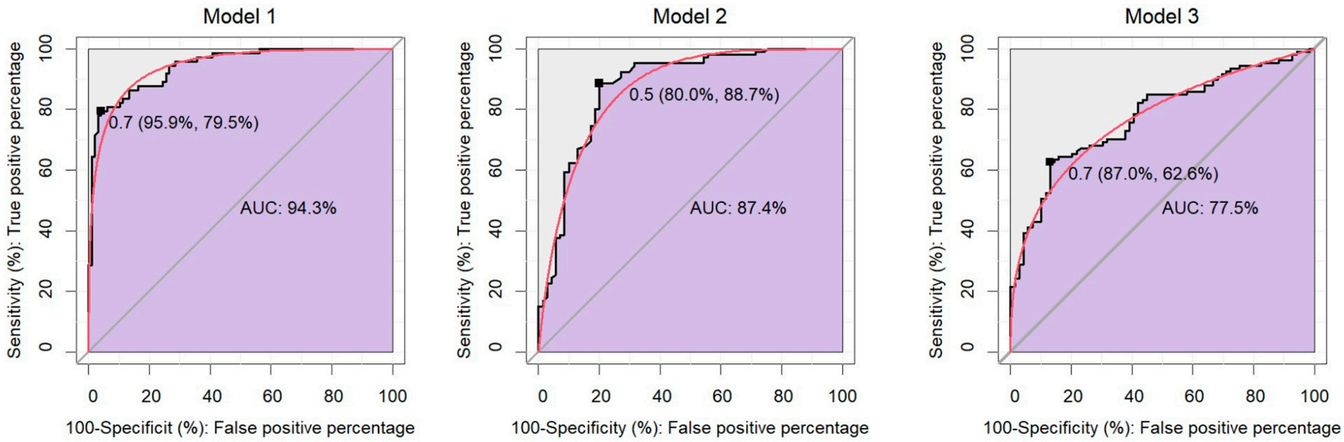

Figure 3. Receiver Operating Characteristic (ROC) curves.

The results revealed that factors such as education, training on water pollution, farm size, urea dose, crop rotation, and awareness of fertilizer use policies significantly ($p < 0.05$) influenced the adoption of pro-environmental fertilization practices (Table 7). Farmers with formal education, training on water pollution issues, who practiced crop rotation, and had awareness of water pollution factors were 4 times, 5 times, 13 times, and 36 times more likely, respectively, to adopt pro-environmental fertilization practices compared with those lacking these attributes (Table 7). In contrast, larger farm sizes (greater than 1 hectare) and higher urea application rates (above 100 kg ha^{-1}) were negatively associated with adoption. The odds ratios of these factors were 0.121 and 0.201, respectively, indicating that farmers with larger farms and those applying higher doses of urea were eight times and five times less likely to adopt pro-environmental practices compared with those with smaller farms and lower urea application rates.

The tree regression analysis identified training on water pollution, farm location within the lowland, and farm size as the most significant factors influencing the adoption of pro-environmental fertilization practices (Figure 4). The decision tree revealed distinct patterns: rice farmers who had received training on water pollution issues demonstrated a high probability (0.78) of adopting pro-environmental practices. Farm location and farm size also emerged as critical determinants. Among farmers who lacked water pollution training but had training in rice cultivation techniques, more than 10 years of farming experience, and fields located downstream in the lowlands, the likelihood of adoption increased to 0.72. Within this group, those managing fields smaller than 1 hectare exhibited an even higher probability (0.88) of adopting these practices. Conversely, farmers with fields located upstream in the lowlands showed a lower tendency to adopt pro-environmental fertilization practices. These results emphasize the importance of tailored interventions that consider the unique characteristics of farmers' training, field location, and farm size to enhance the adoption of sustainable practices (Figure 4).

Table 7. Results for Model 1: adoption of pro-environmental fertilization practices.

Term	Odds Ratio	2.5%	97.5%	Pr(>|z|)
(Intercept)	0.131	0.011	1.306	0.087
Age_group: "36–45"	0.398	0.086	1.692	0.219
Age_group: "46+"	0.589	0.112	2.924	0.520
Education: "Schooled"	3.790	1.252	12.487	0.021 *
Farming.experience_class: "10–19"	2.699	0.709	11.500	0.157
Farming. experience_class: "20+"	4.834	0.749	34.609	0.103
Membership.of.farmers.organization: "yes"	0.880	0.245	2.953	0.837
Training.on.water.pollution: "yes"	5.195	1.159	27.243	0.037 *
Training.on.rice.farming: "yes"	2.189	0.654	7.569	0.204
Farm.location: "middle"	0.919	0.208	3.974	0.910
Farm.location: "downstream"	1.627	0.397	7.023	0.501
Farm.size_class: "1 ha+"	0.121	0.031	0.041	0.001 **
Developed. Field: "yes"	0.302	0.043	1.696	0.197
Urea.dose_class: "76–100"	0.753	0.156	3.459	0.717
Urea.dose_class: "101+"	0.201	0.032	1.089	0.072
Split.urea.application: "Split"	1.521	0.341	6.585	0.570
Choice.criteria: "Fertilizer available on market"	0.336	0.043	2.345	0.280
Choice.criteria: "Field history"	1.632	0.229	12.229	0.625
Choice.criteria: "Arbitrary"	0.986	0.252	3.936	0.984
Crop.rotation: "yes"	13.145	4.250	48.498	<0.001 ***

Notes: Signif. codes: 0 '***'; 0.001 '**'; 0.01 '*'

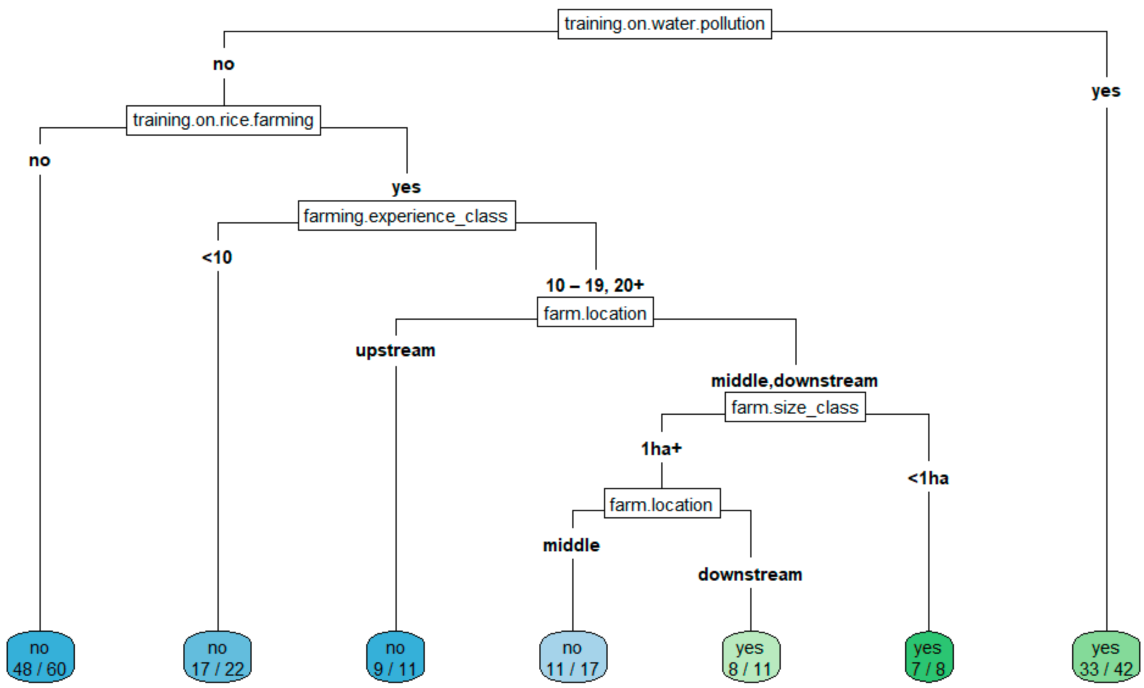

Figure 4. Decision tree on adoption of pro-environmental fertilization practices.

3.4. Rice Farmers' Perception of Water Pollution Risk by Nitrogen and Influencing Factors

The study revealed that rice farmers had a limited understanding of water pollution caused by nitrogen, with only 34.1% acknowledging the issue. Despite this, the majority (60.8%) had observed signs of eutrophication at least once, and nearly 72.2% reported a continuous decline in water quality based on sensory indicators in the outlets of their lowland areas (Table 8). However, few farmers had conducted water quality tests on wells, with the lack of testing attributed to insufficient information (54.9%) and tools (33.4%) for assessing water quality (Table 8). Nevertheless, the majority (68.2%) of farmers were aware that crops do not fully use the total amount of applied fertilizer. The findings indicated that factors such as education level, training on water pollution, and awareness of water pollution factors significantly influenced whether rice farmers recognized the contribution of poor nitrogen fertilization practices to nitrogen-related water pollution in lowland areas (Table 9).

Table 8. Rice farmers' perception of water pollution by nitrogen.

Variables	Characteristics	N (Proportion %)
Do you assess water quality?	No	169 (96.1)
	Yes	7 (3.9)
If no, give the reasons	Lack of information	140 (54.9)
	Lack of device/laboratory	85 (33.4)
	Not important	30 (11.7)
Is all the fertilizer applied used by the crops?	No	120 (68)
	Yes	56 (32)
Do you know that the poor use of fertilizers affects water quality?	No	116 (65.9)
	Yes	60 (34.1)
Perceived eutrophication at the outlets	No	69 (39)
	Yes	107 (60.8)
Perceived the deterioration of sensory quality of water	No	49 (27.8)
	Yes	127 (72.2)

Table 9. Factors affecting farmers' recognition of poor nitrogen fertilization practices inducing water pollution.

Variables	*p*-Value
Gender	0.127
Age	0.121
Education level	<0.001
Have received training on water pollution	<0.001
Farm location	0.988
Dose of urea applied	0.081
Farming experience	0.384
Adoption of pro-environmental practices	<0.001
Knowledge of hydrographic network of the watershed	0.658
Have perceived eutrophication	0.19
Have perceived water organoleptic degradation	0.669
Knowledge of water pollution factors	0.012

3.5. Factors Influencing Rice Farmers' Knowledge of the Hydrographic Network and Observations of Eutrophication

The logit regression for farmers' knowledge of the hydrographic network (Model 2) demonstrated a strong performance, with a highly significant chi-square statistic indicating its superiority over an intercept-only model. The Nagelkerke R-squared value of 0.55 indicated a good model fit, with an accuracy rate of 83.52% (Table 6). The ROC analysis showed an AUC of 87.4%, reflecting robust predictive power (Figure 3). Similarly, Model 3, which predicts factors influencing farmers' observations of eutrophication in lowland outlets, also performed satisfactorily. Its chi-square statistic of 39.43 with 15 degrees of freedom was significant, confirming the model's effectiveness compared with an intercept-only model. The Nagelkerke R-squared value of 0.27 indicated a moderate to good fit, with the model achieving a correctness rate of 73.29% and an AUC of 77.5% in the ROC analysis, underscoring its predictive ability (Figure 3).

The analysis revealed that farmers with more than 10 years of lowland farming experience were 17 times more likely to know the hydrographic network of the watershed compared with those with less than 10 years of experience (Table 10). While the location of the farm within the lowland did not significantly impact farmers' knowledge of the hydrographic network (p-value > 0.05), it did significantly influence their observations of eutrophication. Farmers with fields located downstream and in the middle sections of the lowlands were six times and two times more likely, respectively, to observe the effects of water pollution caused by nitrogen, such as eutrophication, water-related diseases, and changes in the taste of fish products, compared with those with fields in the upstream section of the lowlands (Table 11). Contrary to expectations, socio-demographic variables such as age and education did not significantly influence farmers' knowledge of the hydrographic network or their observations of eutrophication.

Table 10. Summary for logit Model 2: knowledge of hydrographic network by the rice farmers.

Term	Odds Ratio	2.5%	97.5%	Pr(>|z|)
(Intercept)	0.086	0.018	0.355	<0.001
Gender: "male"	0.656	0.269	1.559	0.344
Age_group: "36–45"	1.264	0.454	3.449	0.647
Age_group: "46+"	3.611	1.085	12.424	0.037 *
Education: "Schooled"	1.801	0.681	5.010	0.243
Farming.experience_class: ">10"	16.582	6.270	49.304	<0.001 ***
Training.on.water.pollution: "yes"	1.716	0.635	4.895	0.296
Farm.location: "middle"	0.331	0.101	0.995	0.056
Farm.location: "downstream"	0.718	0.237	2.107	0.549
Knowledge.of.water.leaving.the.field: "yes"	0.826	0.329	2.011	0.676
Knowledge.watershed.outlet: "yes"	3.416	1.334	90.95	0.011 *

Note: Signif. codes: 0 '***'; 0.01 '*'

Table 11. Summary for logit Model 3: observation of eutrophication.

Term	Odds Ratio	2.5%	97.5%	Pr(>∣z∣)
(Intercept)	0.158	0.033	0.707	0.017
Gender: “male”	0.874	0.404	1.860	0.728
Age_group: “36–45”	1.571	0.631	3.996	0.334
Age_group: “46+”	1.702	0.607	4.858	0.313
Education: “Schooled”	1.288	0.551	2.995	0.567
Farming.experience_class: “>10”	1.370	0.519	3.656	0.524
Training.on.water.pollution: “yes”	1.053	0.404	2.786	0.915
Farm.location: “middle”	2.265	0.944	5.590	0.070
Farm.location: “downstream”	6.348	2.547	16.782	<0.001 ***
Urea.dose_class: “76–100”	0.538	0.175	1.516	0.254
Urea.dose_class: “100+”	0.988	0.294	3.176	0.985
Pro.environmental.practices: “yes”	1.057	0.440	2.554	0.900
Knowledge.watershed.network: “yes”	0.861	0.332	2.207	0.756
Have.perceived.water. organoleptic.degradation: “yes”	3.296	1.514	7.380	0.003 **
Knowledge.factors.of.water.pollution: “yes”	1.176	0.524	2.623	0.691
Knowledge.poor.use.of.fertilizers.cause.water.pollution: “yes”	1.783	0.778	4.226	0.177

Note: Signif. codes: 0 ‘***’; 0.001 ‘**’

4. Discussion

4.1. Soil Fertilization Practices of Farmers in Rice Cultivation in Central Benin

Rainfed farming in lowlands remains the predominant rice cultivation system among smallholder farmers in central Benin, consistent with findings by Loko et al. [19]. Most farmers rely on mineral fertilizers such as urea (46% N) and NPK (14:18:18), as reported in previous studies [19,23,25]. In this study, farmers applied an average of 115.2 ± 2.59 kg ha^{-1} of urea (53 kg N ha^{-1}) and 189 ± 2.6 kg ha^{-1} of NPK (26.4 kg N ha^{-1}), resulting in a total nitrogen application of 79.4 ± 1.55 kg N ha^{-1}. This exceeded the recommended rate of 60 kg N ha^{-1}, which corresponds to 75 kg ha^{-1} of urea (34.5 kg N ha^{-1}) and 200 kg ha^{-1} of NPK (28 ± 2 kg N ha^{-1}). Tanaka et al. [25], reported that nitrogen application rates ranged from 31 to 224 kg N ha^{-1}, indicating a wide variation in fertilization. However, their study did not specify an average application rate or its variability, making direct comparisons challenging. Our findings highlight that while nitrogen application in the study area falls within the range documented by Tanaka et al. [25], it is closer to the upper end of the spectrum, suggesting a tendency toward higher nitrogen inputs among the surveyed farmers.

The nitrogen applied by farmers from chemical fertilizer, along with inputs from biological nitrogen fixation (if leguminous plants are cultivated in rotation), manure application, and nitrogen transported by sediments from upland areas, undergoes various transformation processes [95]. Mineralization and nitrification–denitrification convert organic nitrogen into ammonium and nitrate, which are directly available for plant uptake. However, when nitrogen application exceeds crop requirements or is not synchronized with plant demand, significant losses can occur [96]. Excess nitrogen which is not fixed in the soil can leach into groundwater and runoff into surface water, contributing to water pollution.

The gap between recommended and actual nitrogen application rates can be attributed to several factors, including soil degradation, financial constraints, and farmers’ efforts to maximize yields [22,25,65]. Our study identified field location within the lowlands and crop rotation practices as primary factors influencing urea application variability. Variations in soil nutrient content along the toposequence likely explain these differences [35]. Downstream fields, enriched with nutrient from upstream fields, emphasize the role of field location in fertilization decisions. Contrary to other studies [65,97], socio-demographic variables, such as age, education level, and gender, did not significant impact fertilization practices. Similarly, gender, which is often considered a determining factor, does not appear to substantially influence fertilization practices, aligning with findings by Doss and Morris [98]. Our study also reveals that most lowland rice farmers (81.9%) used the broadcasting method for fertilizer application. This method is known to increase nitrogen losses due to its inefficiency in targeting the root zone. In contrast, the deep placement of nitrogen fertilizers concentrates available nitrogen in the root zone, reducing nitrogen losses and enhancing crop uptake [99].

Inefficient fertilization practices negatively impact yield and nitrogen use efficiency and increase environmental pollution risks in Sub-Saharan Africa [100]. These findings highlight the need for tailored nutrient management strategies to optimize fertilizer use, reduce costs, and mitigate environmental harm. Farmers who received formal education, training on water pollution issues, practiced crop rotation, and had awareness of water pollution factors were significantly more likely by 4, 5, 13, and 36 times, respectively, to adopt pro-environmental fertilization practices. However, the adoption of such practices remains low [35]. While some studies highlight the importance of farmers' education levels and economic status [101], these may not sufficiently promote environmentally friendly practices unless coupled with environmental awareness initiatives [102]. Targeted training on water pollution issues can significantly enhance the adoption of pro-environmental practices, even under economic constraints. Furthermore, the actual effectiveness or profitability of adopting best practices must be fully established to encourage broader adoption by farmers [35,103].

4.2. Rice Farmers' Perceptions and Factors Influencing Awareness of Nitrogen-Related Water Pollution Risks

In Sub-Saharan Africa, surface and groundwater contamination by organic matter, nitrates, phosphates, and pesticides has been reported [104,105]. The eutrophication of lakes and rivers, often marked by the proliferation of water hyacinths, is a common issue [104]. This phenomenon is primarily driven by anthropogenic activities, particularly excessive nutrient loads, including nitrates and phosphorus, in water bodies [106]. Omo-Irador et al. [107] reported that the presence of nitrates, sodium, potassium, and magnesium in water is mainly linked to agricultural and domestic pollution sources.

Monitoring water quality is essential for developing effective management strategies, mitigating pollution risks, reducing pressure on water resources, and supporting informed decision making [34,35,108]. However, our study revealed that water quality monitoring in the region remains minimal. This finding aligns with previous research highlighting the limited capacity for water quality assessment in Africa [12,102].

Our findings indicate that rice farmers often lack awareness of the impact of nitrogen fertilizer mismanagement on water pollution. Despite 60.8% of rice farmers reporting visible signs of eutrophication at lowland outlets, only 34.1% recognize poor nitrogen fertilizer management as a contributing factor to water pollution. This discrepancy highlights a gap between observing pollution symptoms and understanding their causes. Similar findings were reported by Ilboudo et al. [12], who noted that while farmers can detect water degradation through visual indicators such as changes in aquatic vegetations, water color, and odor, they often lack knowledge of the underlying causes. In contrast, studies conducted in Nitrate Vulnerable Zones (NVZs) of the EU indicate that farmers are generally aware of water quality issues and acknowledge agriculture as a potential source of pollution, even if they do not always recognize their own contributions [33,35,46]. This differs from the situation in Sub-Saharan Africa, where farmers' perception of water pollution risks remains relatively low.

Our study highlights the critical role of education in improving farmers' awareness and understanding of water pollution issues. This finding aligns with studies on farmers' perceptions of climate change and their adaptive strategies, which emphasize the importance of education in improving knowledge of agricultural practices and associated risks [22,109,110]. Additionally, targeted training programs on water pollution and proper fertilizer use can significantly improve farmers' comprehension and encourage the adoption of best practices. Farmers often need clear and concise information to reassess their perceptions and adjust their practices accordingly [111].

Addressing knowledge gaps and strengthening farmers' ability to assess water quality can improve management practices, reduce pollution, and support sustainable agriculture in lowland areas. Key actions include revising technical production guides to incorporate water quality modules, establishing a citizen science water quality monitoring network using test strips, and integrating water quality education into training programs. Once farmers recognize these risks, they will be better equipped to adopt pro-environmental practices. Furthermore, fostering collaboration among experienced rice farmers, less experienced farmers, and agricultural extension agents can facilitate knowledge sharing and improve adoption rates of sustainable practices. This process requires strengthening the structural framework of national agricultural development agencies to enhance their effectiveness in supporting and training farmers. Such measures will contribute to better-informed farmers, encourage the widespread dissemination of best practices, and promote the adoption of sustainable agricultural techniques.

4.3. Limitations and Perspectives

This study used a survey-based approach with personal interviews to understand the fertilization practices of rice farmers in lowland areas of central Benin. It also identified key factors influencing farmers' decisions to adopt specific nitrogen fertilization methods and their perceptions of water pollution. However, three key limitations should be considered for future research on this topic in Sub-Saharan Africa.

The first limitation concerns the data collection method. We relied solely on personal interviews, which, while valuable, could be complemented by field surveys during the growing season [25]. Such an approach would allow for the collection of additional quantitative data to better assess fertilization practices and farmers' perceptions.

The second limitation relates to the study's geographical scope. We focused on a single climatic zone of central Benin, yet local agroecosystem conditions, such as climate, may influence farmers' behavior and the adoption of sustainable agricultural practices [37,112]. Understanding these dynamics could help to improve knowledge transfer and encourage the adoption of environmentally sustainable fertilization practices.

The third limitation of this study lies in the fact that we used the recommended fertilizer doses for lowland rice cultivation in Benin as a reference. These doses are generally determined based on response curves to nutrients (N, P, and K) and the calculation of the amounts needed to achieve a target yield [23]. However, in many African countries, these recommendations may often be general or outdated [113]. Given the impacts of climate change, the rotation of crops year after year, and the evolving intrinsic nutrient potential of agricultural soils, it is crucial that fertilizer recommendations are regularly updated. This would help to better adapt to the dynamics of cultivated lands. This finding reinforces the previously expressed idea regarding the need to revise the guides intended for farmers. It also highlights the importance, for future research, of investigating the territorial issues related to agricultural development by actively involving farmers in the development of these guides through a participatory approach.

5. Conclusions

Our study revealed that lowland rainfed rice is the predominant rice farming system in the study area. Nearly all rice farmers use mineral fertilizers. Given the environmental and agronomic challenges associated with these fertilizers, we recommend promoting the dissemination of agroecological practices in lowland rice-based farming systems. The findings highlight the significant role of field characteristics in the adoption of fertilization practices. Fertilization levels varied between upstream and downstream areas within the same lowland, underscoring the need for improved nutrient management. This calls for the implementation of specific land management strategies to ensure a more balanced distribution of nutrients both longitudinally and transversally across the lowland. Practical recommendations for rice farmers include constructing small bunds and subdividing their fields to optimize surface water distribution and retain nutrients carried by runoff. Additionally, planting grasses on bunds can enhance their stability and reduce erosion, while integrating leguminous plants such as Tithonia can provide a natural source of green manure. Crop rotation should also be encouraged as part of a sustainable soil fertility management strategy.

Regarding the adoption of recommended fertilizer application rates, our study identified a gap between national recommendations and actual rice farmer practices. This discrepancy highlights the need for national extension agencies to update their technical packages and improve monitoring processes to ensure better compliance with fertilization guidelines.

Concerning the farmer's perception on water pollution risks from nitrogen residues, the study found that while farmers acknowledge the existence of pollution risks, they do not necessarily associate them with their fertilization practices. However, farmers who have received specific training on drinking water quality and those with more experience tend to have a better understanding of these risks and adjust their practices accordingly. This underscores the importance of designing farmer education programs that incorporate environmental protection principles, particularly water quality preservation. Such programs should not focus solely on improving production techniques and increasing yields but should also emphasize sustainability and ecosystem conservation. Encouraging knowledge transfer between experienced and novice farmers, as well as establishing farmer-led water quality monitoring systems at the outlets of the lowland, would help to raise awareness of pollution risks and encourage behavioral changes regarding certain practices. The use of citizen science approaches, such as water quality monitoring with test strips, could enhance understanding of water pollution issues and foster pro-environmental practices.

This study highlights the challenges faced by lowland rice farmers in Benin regarding fertilization practices and water pollution risks. It emphasizes the urgent need for targeted extension programs to raise awareness and promote environmentally friendly practices. Optimizing fertilizer use through adjusted application rates, regular soil monitoring, and tailored nutrient management strategies is essential for sustainable agriculture. By addressing these gaps, we can support sustainable rice cultivation in Benin's lowland ecosystems and ensure their preservation for future generations.

Author Contributions: Conceptualization, S.K.G., P.G.T., P.B.I.A. and M.V.; data curation, S.K.G.; formal analysis, S.K.G.; methodology, S.K.G., P.G.T., P.B.I.A. and M.V.; software, S.K.G.; supervision, P.G.T., P.B.I.A. and M.V.; validation, P.B.I.A. and M.V.; visualization, P.G.T., P.B.I.A. and M.V.; writing—original draft, S.K.G.; writing—review and editing, S.K.G., P.G.T., A.A., P.B.I.A. and M.V. All authors have read and agreed to the published version of the manuscript.

Funding: We acknowledge the funding from UCLouvain's Conseil de l'Action Internationale (CAI) South Partnership and Wallonie-Bruxelles International (WBI).

Data Availability Statement: Data will be made available on request.

Acknowledgments: We sincerely thank Wallonie-Bruxelles International (WBI) for its commitment to supporting development and research projects in Benin, particularly through the BAFONBE and APROPO projects. Our gratitude also extends to the BAFONBE lowland committees for their active collaboration during the survey phase. We are thank to Thomas AKPONIKPE, Armand YAHOU, and Jean-Baptiste FANOU, agricultural technicians and surveyors, for their invaluable contributions to data collection. Finally, we warmly thank the rice farmers in the villages for their interest and collaboration in this study.

Conflicts of Interest: The authors declare no conflicts of interest.

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