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Factors Influencing Adoption of the PlantVillage Nuru Application for Cassava Mosaic Disease Diagnosis Among Farmers in Benin

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Abstract: Cassava production in Africa is constrained by number of biotic factors, including cassava mosaic disease (CMD). In response to this challenge, the PlantVillage Nuru application, which employs artificial intelligence for CMD diagnosis, provides farmers with the ability to independently detect the disease. This study examines the factors influencing the adoption of the innovative Nuru application by farmers in Benin. Data were randomly collected from 305 farmers in three Agricultural Development Poles (PDAs 5, 6 and 7). A binary logit model was used to analyze the determinants of adoption. The results show that, despite the potential of the Nuru application, the adoption rate remained relatively low at 14.1%. The key drivers of adoption were found to be participation in CMD training, disease knowledge, ownership of an Android smartphone, education level and practice of crop association. These findings emphasize the necessity of intensifying farmers' training and raising awareness about CMD. Effective strategies to reach and train a significant number of farmers are crucial. Enhancing Nuru adoption can lead to more effective CMD management and improved cassava production, which will have a positive impact on food security in Africa and strengthen the resilience of farming communities against biotic challenges.

Keywords: cassava mosaic disease; PlantVillage Nuru; adoption decision; logit model

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Citation: Ahoya, D.K.D.; Sawadogo-Compaore, E.M.F.W.; Yabi, J.A.; Zandjanakou-Tachin, M.; Houngue, J.A.; Houedjissin, S.S.; Pita, J.S.; Ahanhanzo, C. Factors Influencing Adoption of the PlantVillage Nuru Application for Cassava Mosaic Disease Diagnosis Among Farmers in Benin. *Agriculture* **2024**, *14*, 2001. https://doi.org/10.3390/agriculture14112001

Academic Editor: Sanzidur Rahman

Received: 9 September 2024
Revised: 30 September 2024
Accepted: 10 October 2024
Published: 7 November 2024

1. Introduction

Infectious plant diseases significantly affect global agricultural production and lead to substantial economic losses [1]. Among these, cassava mosaic disease (CMD) stands out as a major threat to cassava cultivation. CMD can cause a fresh root yield reduction ranging from 20 to 95% [2], resulting in estimated economic losses between USD 1.9 and 2.7 billion [3]. This disease is caused by Begomoviruses, a group of plant viruses belonging to the *Geminiviridae* family [3]. They are transmitted by whiteflies (*Bemisia tabaci*) and spread by human-mediated vegetative propagation through the exchange of infected planting material [4].

A recent survey conducted on cassava farms in Benin revealed that 81% of these farms were infected with CMD [5]. This prevalence of CMD is primarily attributed to the use of infected planting material by farmers, rather than whiteflies. Indeed, it was found that nearly 93.51% of cassava farmers obtain their planting material from their own fields or neighboring fields [6]. In most cases, this planting material is obtained without the verification of symptoms in the leaves of the mother plant by farmers, which favors the maintenance of infected plants in production areas. Additionally, it was demonstrated that the majority of cassava farmers lacked awareness that infected planting material could act as an additional source of viral disease spread in their fields, subsequently affecting the fields of neighboring farmers [7]. This lack of knowledge or ignorance during the selection of planting material by farmers represents a significant threat to cassava cultivation, which is evident in the rapid spread/propagation of viral diseases in all regions of the country [6]. Furthermore, the asymptomatic state of the leaves of some cassava plants, which are nevertheless carriers of CMD, presents a challenge for farmers in recognizing this disease [8].

In response to the challenges faced by farmers and extension agents in correctly identifying viral diseases of cassava, scientists from Penn State University have collaborated with other researchers working on roots and tubers to develop an innovative solution: the intelligent application for the real-time detection of cassava viral diseases, PlantVillage Nuru [9]. PlantVillage Nuru is an artificial intelligence (AI)-assisted mobile application that operates within a standard smartphone and is capable of accurately diagnosing cassava diseases offline, without an internet connection [10]. This mobile application serves as a valuable tool for farmers, facilitating rapid identification and decision-making in plant disease control [1]. The autonomous detection capabilities of the application provide actors within the cassava sector with the ability to make informed decisions in a timely manner, thereby reducing the losses caused by these destructive diseases [10]. By preventing the use of infected cuttings in new cassava fields, PlantVillage Nuru contributes to the reduction of disease spread throughout the region, which benefits the entire agricultural community by decreasing overall crop losses. Furthermore, the effective management of CMD is essential for ensuring the stability of cassava production, which is a crucial component of local and regional food security. The adoption of new technologies, such as PlantVillage Nuru, has the potential to generate positive externalities that benefit neighboring farmers and the wider community [11].

Since 2022, a series of campaigns has been conducted by the Central and West African Virus Epidemiology (WAVE: https://wave-center.org/ (accessed on 13 May 2024) in Benin and in the member countries in Central and West Africa with the objective of raising awareness and training the actors of the cassava sector (farmers, seed multipliers, extension agents, etc.) in the use of the PlantVillage Nuru application. The adoption of this technology by these actors should allow for the effective management of CMD in Benin and increase cassava productivity throughout Africa. However, the technical performance of the innovation is unfortunately not sufficient to justify its use and guarantee its adoption by the actors. Several studies have shown that the adoption of agricultural technologies generally depend on several factors. These include the characteristics of the farmers, the environment, the knowledge of the innovation and the specific attributes of the innovation [12,13]. These factors influence the adoption rate of these technologies. However, it is currently unclear which of these factors play a significant role in the adoption by farmers of the PlantVillage Nuru application in Benin. It is therefore necessary to seek to understand the factors that determine the adoption of this application in order to facilitate its acceptance by farmers and to improve the management of cassava viral diseases, particularly CMD. Therefore, the objective of this study is to identify the factors influencing the adoption of the PlantVillage Nuru application by cassava farmers in Benin.

2. Materials and Methods

2.1. Theoretical Framework for the Adoption of the PlantVillage Nuru Application

The adoption of new technologies is a complex process that has been studied using various models and theories [14]. In the agricultural context, the PlantVillage Nuru application represents a major technological innovation. To understand its adoption, we use the theory of diffusion of innovations [15].

The theory of diffusion of innovations [15] provides an appropriate framework for examining the adoption of the PlantVillage Nuru application by farmers. According to this theory, diffusion is the process by which an innovation is communicated over time among the members of a social system through certain channels. Rogers identified the following five attributes of innovation that influence the adoption rate:

1. Relative Advantage: This is the degree to which an innovation is perceived as superior to the idea it replaces. In the context of our study, this translates to the perceived benefits of adopting the PlantVillage Nuru application compared to traditional methods of identifying symptoms and managing cassava diseases. The Nuru application provides a significant advantage by allowing farmers to quickly and accurately diagnose plant diseases, such as cassava mosaic disease, using just their smartphones [10]. This technology can reduce crop losses and increase yields, making it a major economic benefit.
2. Compatibility: This is the extent to which an innovation is perceived as being compatible with existing values, past experiences and the needs of potential adopters. This could be explored by examining how the application integrates into existing agricultural practices and the value systems of farmers.
3. Complexity: This is the degree to which an innovation is perceived as difficult to understand and use. This could be evaluated by examining the ease of use of the application and the availability of training and support. The Nuru application has been designed with the intention of being user-friendly, even for farmers with limited technological skills. The user interface is intuitive, and the instructions are clear, which serves to reduce the perceived complexity [11].
4. Trialability: This is the extent to which an innovation is subjected to a limited scale trial prior to its full adoption. In order to assess the trialability of an innovation, it is essential to ascertain whether farmers are able to implement it on a small scale prior to making a definitive commitment to it. To illustrate this, in the case of the Nuru application for the management of cassava diseases, farmers could utilize it to diagnose diseases on a limited portion of their field. They could then compare the results obtained with those derived from traditional methods. This approach would permit them to evaluate the efficacy of the application before implementing it on a larger scale.
5. Observability: This refers to the degree to which the results of an innovation are visible to others. It can be assessed by examining how the positive effects of using the application are shared and observed by other farmers. In the case of the Nuru application, neighboring farmers who utilize the app may notice a decrease in disease symptoms and an overall improvement in plant health. This visibility makes the benefits of the Nuru application readily observable.

The application of the theory of diffusion of innovations to the adoption of the PlantVillage Nuru application allows the formulation of several hypotheses. For instance, it can be expected that farmers who have easy access to information and who are more open to new experiences are more likely to adopt the application.

2.2. Study Area

The study was conducted in the Agricultural Development Poles (PDAs) 5, 6 and 7 of Benin. These three (03) PDAs were selected for the following reasons: (i) they are suitable areas for cassava production and represent more than 60% of the national cassava production [16]; (ii) the series of awareness campaigns and training of cassava sector actors on the use of the PlantVillage Nuru application has been implemented in these PDAs; and (iii) recent surveys have demonstrated the prevalence of CMD in the majority of cassava fields in these PDAs [5]. Figure 1 presents a map of the study area.

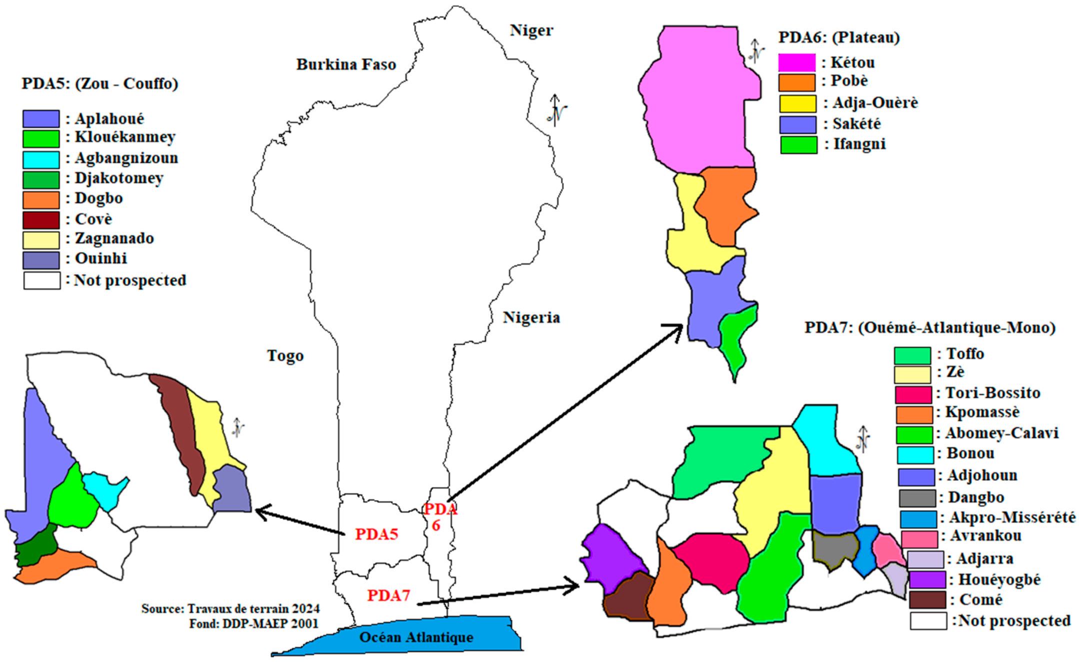

Figure 1. Map showing the study area.

2.3. Data Collection

The data for this study were collected via the administration of a questionnaire to farmers through a multi-stage sampling process. The initial stage of the process involved the selection of the Agricultural Development Poles (PDA). Subsequently, six departments within the aforementioned PDAs were selected: Atlantique, Couffo, Mono, Ouémé, Plateau and Zou. Within these departments, communes were randomly selected based on the proportion of cultivated area and cassava production. For each selected commune, a list of cassava farmers was obtained from the Communal Cell Chief (Chef de Cellule Communal, CCeC). Farmers were randomly selected based on their availability. The sample size in each commune was dependent on the number of farmers who responded to the calls from the officials of the Communal Cell of the said commune (Table 1). In total, 305 cassava farmers were surveyed.

Table 1. PDA, departments, communes and sampled farmers participating in the survey in 2024.

PDA	Department	Commune	Number of Sampled Farmers
PDA 5 (Zou–Couffo)	Couffo	Aplahoué	13
		Djakotomey	11
		Dogbo	11
		Klouékanmey	10
	Zou	Agbangnizoun	6
		Covè	10
		Ouinhi	14
		Zagnanado	12
PDA 6 (Plateau)	Plateau	Adja-Ouèrè	13
		Ifangni	10
		Kétou	14
		Pobè	16
		Sakété	17

Table 1. *Cont.*

PDA	Department	Commune	Number of Sampled Farmers
PDA 7 (Ouémé–Atlantique–Mono)	Atlantique	Abomey-Calavi	12
		Kpomassè	11
		Toffo	11
		Tori-Bossito	14
		Zè	11
	Ouémé	Adjohoun	11
		Akpro-Missrété	11
		Adjarra	9
		Avrankou	11
		Bonou	13
		Dangbo	9
	Mono	Comè	12
		Houéyogbé	13
Total			305

The questionnaire administered to cassava farmers was digitized using the Kobotoolbox (v2024.1.3) software. It is structured around the demographic and socio-economic characteristics of farmers, the technical systems of cassava production in agricultural farms, the knowledge of viral diseases of cassava, the strategies for managing these diseases and the use of the PlantVillage Nuru application. Prior to the administration of the questionnaire, it was pre-tested by the selected enumerators through interviews with other farmers not included in the survey. This process aimed to evaluate the questionnaire's performance and ensure the adequacy of the information necessary to achieve the objectives of the study. During the actual data collection, the objectives and importance of the survey were communicated to the farmers to obtain their permissions and consents for their participation in the study before administering the questionnaire. The data were collected in February 2024.

2.4. Econometric Model

In order to ascertain the factors that may explain the adoption of the intelligent application PlantVillage Nuru, which was introduced by WAVE for the management and control of CMD in Benin, a binary logistic regression model (LRM) was selected. The binary logistic regression model was selected as it is an appropriate method for describing the relationship between a binary dependent variable (adopt/not adopt) and a set of independent or explanatory variables [13,17]. In the context of this study, the binary logistic regression model is a useful tool for determining the reasons that explain why a farmer adopts or does not adopt the PlantVillage Nuru application. In this model, the variable y^* is defined as follows:

$$y_i^* = \propto + X_i \beta + \varepsilon_i \quad (1)$$

where y_i^* represents the interest (benefits or advantages) derived by the farmer from their choice to adopt the PlantVillage Nuru application; $\propto$ refers to the constant and represents the expected value of the dependent variable when all independent variables are zero; X_i is a variable that can influence the use of the application; β represents the coefficients associated with the different variables of the model; and ε_i is the error associated with the variable. Since the variable y_i^* is not observable, it is necessary to generate an observable variable expressing the choice of a strategy by a farmer:

$$\begin{cases} y = 1, if\ the\ farmer\ adopts\ the\ PlantVillage\ Nuru\ application \\ y = 0,\ if\ the\ farmer\ does\ not\ adopt\ the\ PlantVillage\ Nuru\ application \end{cases}$$

As outlined by [18], the regression of the logit model characterizing the choice by a sample of farmers is specified as follows:

$$P_i = E(y_i) = F(\propto + X_i\beta)_{-}\frac{1}{\left[1 + e^{-(\propto + X_i\beta)}\right]} \quad (2)$$

where i indicates the i^{me} observation in the sample, P_i is the probability that an individual makes a given choice, y_i is the base of the natural logarithm, X_i is a vector of exogenous variables, $\propto$ is a constant, and β represents the coefficients associated with each explanatory variable, X_i, to be estimated. The sign of the coefficients indicates the direction of the effect of the explanatory variables on the adoption of the PlantVillage Nuru application. The estimation of the coefficients $\propto$ and β in the regression was carried out using the method of maximum likelihood [19].

2.5. Explanatory Variable of the Econometric Model

The variables included in the econometric model were selected based on a synthesis of theoretical and empirical literature regarding the adoption of agricultural technologies, as well as the availability of relevant data [12,17,20]. Consequently, Table 2 presents the variables that are hypothesized to influence the adoption of the intelligent application PlantVillage Nuru by farmers.

Table 2. Definition of variables and their probable effects in the econometric model.

Variables	Description and Justification for the Variable Selected	Expected Signs
	Dependent variables	
Adoption of the intelligent application PlantVillage Nuru (ADOPTNURU)	0—Non-adoption of the intelligent application PlantVillage Nuru and 1—Adoption of the PlantVillage Nuru application	
	Independent Variables	
Age of the farmer (AGE)	The age of the farmer is a continuous variable. It is possible that younger farmers may exhibit risk aversion and be less inclined to adopt new technologies. Conversely, older farmers may possess greater experience and resources that could facilitate the adoption process [21]. This implies that age may be a significant factor in the adoption of new technologies, such as the PlantVillage Nuru application, among farmers.	+/−
Gender (GEN)	Dichotomous variable (0 = Female; 1 = Male). Gender plays a significant role in technology adoption due to disparities in access to information and extension services between men and women. However, our hypothesis is that men are more likely to adopt the Nuru application than women. This belief is based on the premise that women often have limited access to smartphones and the internet compared to men, which could potentially hinder their ability to use applications like PlantVillage Nuru [11].	−
Education level (EDULEVEL)	Discrete variable with four categories: (i) Unschooled; (ii) Primary; (iii) Secondary; and (iv) Higher/Tertiary. Education plays a pivotal role in enabling farmers to effectively acquire and synthesize information and knowledge about the problem and technologies, which is a crucial factor in the adoption of technologies [17]. It should be noted that the intelligent application PlantVillage Nuru requires a minimum level of understanding of the French language.	+

Table 2. *Cont.*

Variables	Description and Justification for the Variable Selected	Expected Signs
Marital status (MARSTATUS)	The marital status of an individual can influence their access to resources, decision-making abilities and the distribution of work within the household. These factors can subsequently affect the adoption of new technologies. In this context, the authors of Ref. [13] have demonstrated that marital status exerts a positive influence on the adoption of agroforestry.	+/−
Possession of an Android phone (ANDROID)	This is a dichotomous variable defined as a categorical variable with two possible values (0 = No and 1 = Yes). PlantVillage Nuru is an intelligent application that is only compatible with Android devices [10].	+
Distance between the field and the house (FIELDDIST)	This is a continuous variable. The distance between the field and the house may have a positive or negative influence on the adoption of the PlantVillage Nuru application. Indeed, if the field is situated in close proximity to the house, it may be more convenient for the farmer to conduct regular monitoring of their field and utilize the application to identify diseases. Additionally, the quality of the internet connection may vary depending on the location of the field.	+/−
Cassava production area (CASPRODAREA)	The cassava production area is a continuous variable. It is plausible to suggest that farmers with a larger cassava production area may be more inclined to adopt the application to monitor and manage CMD in their fields. This would permit them to conserve time by promptly identifying cassava diseases on their farms. Consequently, the extent to which the cassava production area may have a positive or negative influence on the adoption of the PlantVillage Nuru application remains to be seen.	+/−
Crop association or intercropping (CROPASSOC)	Dichotomous variable (0 = No and 1 = Yes). The practice of crop association has been identified as a potential risk factor that could potentially increase the incidence of CMD in cassava fields [5]. Consequently, farmers who have previously engaged in intercropping may be more likely to adopt the PlantVillage Nuru application.	+
General knowledge about CMD (CMDKNOWLEDGE)	The general knowledge of CMD (continuous variable) was quantified by calculating the ratio between the score obtained and the total possible score. The score was determined by aggregating the following sub-components: identification of symptoms, knowledge of the name of the disease, knowledge of the cause of the disease, knowledge of the mode of disease propagation and knowledge of disease prevention strategies [22]. Consequently, the final score represents the overall level of disease knowledge. It can be reasonably assumed that farmers with a high level of disease knowledge are more likely to adopt disease control and management measures [12]. Furthermore, a comprehensive grasp of CMD could empower farmers to more effectively interpret the information provided by the application, thereby facilitating informed decision-making regarding the management of their crops. This suggests that the general knowledge about CMD could play a significant role in the use of the PlantVillage Nuru application.	+
Participation in training and awareness sessions (TRAINPARTIC)	This is a dichotomous variable (0 = No and 1 = Yes). The participation of farmers in awareness and training campaigns on the use of the PlantVillage Nuru application allows them to become aware of the application, its use and its importance in the management of CMD. This indicates that participation in such campaigns could be a pivotal factor in the adoption of the PlantVillage Nuru application.	+

2.6. Test of Multicollinearity

Multicollinearity in regression analysis refers to a situation where there is a high correlation among predictor variables. This condition can result in an increase in the variance of the estimated regression coefficients, rendering them unstable and unreliable [23,24]. The presence of multicollinearity can be identified by examining the correlation matrix of the predictor variables or by calculating the variance inflation factors (VIFs) for the regression coefficients [23]. In this study, we addressed the issue of multicollinearity by estimating the variance inflation factors (VIFs) for each predictor variable. A threshold of less than 2.5 for the VIF was employed as a criterion for detecting multicollinearity, in accordance with the recommendations presented in prior studies [25,26]. This approach permitted the inclusion of only those independent variables exhibiting low intercorrelations in the model.

2.7. Data Analysis

All statistical analyses, including descriptive statistics, model parameter analyses and the regression model, were conducted using the STATA 17 software.

3. Results

3.1. Characteristics of Farmers

The summary of the characteristics of the surveyed farmers as well as their general knowledge about CMD is presented in Table 3.

Table 3. Descriptive statistics of the farmers' characteristics.

Qualitative Variables	Modalities	Percentage			p-Value
		Entire Sample (n = 305)	Adoption of Nuru (n = 43)	Non-Adoption of Nuru (n = 262)	chi2
Gender	Male Female	82.95 17.05	95.35 4.65	80.92 19.08	0.020
Marital status	Single Married Widowed	3.28 95.74 0.98	4.65 93.02 2.33	3.06 96.18 0.76	0.537
Education level	Unschooled Primary Secondary Higher	33.11 20 34.75 12.14	11.64 18.6 44.18 25.58	36.64 20.23 33.21 9.92	0.001
Number of years in cassava production	1 to 5 years 6 to 10 years 11 years plus	13.77 23.61 62.62	11.63 32.56 55.81	14.12 22.14 63.74	0.327
Possession of an Android phone	Yes No	73.11 26.89	97.67 2.33	69.08 30.92	0.000
Member of a cassava association	Yes No	60.66 39.34	72.09 27.91	58.78 41.22	0.098
Quantitative Variables			**Mean (Standard error)**		**t-test**
General knowledge about CMD (score)		5.47 (0.19)	9.56 (0.24)	4.79 (0.18)	0.000
Age of farmers (years)		44.92 (0.68)	43.83 (1.83)	45.09 (0.73)	0.518
Size of households		8.25 (0.28)	8.09 (0.75)	8.28 (0.30)	0.813
Cassava production area (ha)		2.63 (0.23)	3.21 (061)	2.53 (0.24)	0.295
Distance field–house (km)		7.25 (0.35)	7.18 (1.13)	7.26 (0.36)	0.931

Out of the 305 farmers surveyed, Table 3 indicates that the percentage of farmers who have adopted the PlantVillage Nuru application is low (14.1%) compared to non-adopters (85.9%). The majority of those who have adopted the application are male (95.35%), with an average age of 44 years. Most of the adopters have at least completed primary school and are married (93.02%). The average size of their households is 8 members, with an average of 3.21 ha of land dedicated to cassava production. Moreover, the majority of those who have adopted the application (97.67%) own an Android phone and have a better understanding of the disease (score of 9.56) than non-adopters (score of 4.79). The mean distance between their home and the field is 7.18 km. The majority of the application adopters (72.09%) are members of a communal or departmental association of cassava producers and have accumulated more than 10 years of experience in cassava production.

3.2. Factors Determining the Adoption of the PlantVillage Nuru Application

The econometric model, which integrates a number of independent variables (sociodemographic characteristics of farmers, general knowledge score of CMD, etc.), is presented in Table 4. This table shows that the model used in this study is significant at the 1% level with a pseudo-R2 value of 0.537. This value indicates that 53.7% of the variability in the adoption of the PlantVillage Nuru application by farmers in PDAs 5, 6 and 7 in Benin is explained by the variables included in the model. The results demonstrated that five significant factors or variables (p-value < 5%) effectively determine the adoption of this application by cassava farmers. The results indicate that participation in CMD training and awareness sessions, possession of an Android mobile phone, level of education (secondary level), good knowledge of CMD and the practice of crop association are significant factors influencing the adoption of this application by cassava farmers. However, gender, the farmer's age, the area used for cassava cultivation, the distance between home and fields, and the farmer's marital status did not have a significant effect on the adoption of this application.

Table 4. Estimation of the logit model for the adoption of the PlantVillage Nuru application (Yes = 1, No = 0) for each of the predictive variables.

Independent Variables	Coef.	Odds Ratio	St. Err.	t-Value	p-Value	[95% Conf	Interval]	Sig
TRAINPARTIC	1.977	7.218	0.599	3.30	0.001	0.803	3.15	***
CMDKNOWLEDGE	0.604	1.829	0.138	4.38	0.000	0.334	0.874	***
ANDROID	2.914	18.436	1.176	2.48	0.013	0.609	5.219	**
EDULEVEL	0	1	-	-	-	-	-	
Primary	0.104	1.11	0.776	0.13	0.893	−1.416	1.625	
Secondary	1.266	3.547	0.739	1.71	0.087	−0.182	2.714	*
Higher	1.326	3.766	0.957	1.39	0.166	−0.55	3.202	
GEN	0	1	-	-	-	-	-	
Female	−0.572	0.564	0.988	−0.58	0.563	−2.509	1.365	
CROPASSOC	0	1	-	-	-	-	-	
Crop association	1.528	4.608	0.621	2.46	0.014	0.311	2.744	**
AGE	−0.018	0.983	0.026	−0.68	0.494	−0.068	0.033	
MARSTATUS	0	1	-	-	-	-	-	
Married	−0.69	0.502	1.138	−0.61	0.545	−2.921	1.541	
Widowed	5.056	156.912	8.73	0.58	0.563	−12.055	22.166	
FIELDDIST	−0.0032	0.969	0.035	−0.90	0.37	−0.101	0.037	
CASPRODAREA	0.048	1.049	0.042	1.14	0.255	−0.035	0.131	
Constant	−10.516	0	2.496	−4.21	0	−15.408	−5.624	***
Mean dependent var			0.141			SD dependent var		0.349
Pseudo r-squared			0.537			Number of obs		305
Chi-square			133.154			Prob > chi2		0.000
Akaike crit. (AIC)			142.961			Bayesian crit. (BIC)		195.045

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

The analysis of marginal effects by statistically significant independent variables in Table 5 indicates that, all other things being equal, the probability of the respondents adopting the PlantVillage Nuru application is 0.878 when the respondents have participated in CMD training and awareness sessions, 0.647 when the respondents have a good knowledge of CMD, 0.946 when they own an Android mobile phone, 0.78 when they have a secondary level of education and 0.822 when the respondents practice cultural association.

Table 5. Odds ratio, probability of adoption of the PlantVillage Nuru application and confidence interval based on significant independent variables.

	Coeff.	Marginal Effect (dy/dx)	Odds Ratio (e^{β})	Prob. ($P = e^{\beta}/(1+e^{\beta})$)	$p > z$	[95%
TRAINPARTIC	1.977	0.115	7.218	0.878	0.056	0.175
CMDKNOWLEDGE	0.604	0.035	1.829	0.647	0.022	0.049
ANDROID	2.914	0.170	18.436	0.946	0.043	0.297
EDULEVEL	0		1			
Primary	0.104	0.005	1.11	0.53	−0.072	0.083
Secondary	1.266	0.073	3.547	0.78	−0.005	0.151
Higher	1.326	0.077	3.766	0.79	−0.033	0.187
CROPASSOC	0		1			
Crop association	1.528	0.085	4.608	0.822	0.026	0.144

4. Discussion

4.1. Analysis of the Proportion of Adopters and Non-Adopters of the PlantVillage Nuru Application

The proportion of adopters of the PlantVillage Nuru application in the study area is low compared to non-adopters (Table 4). The low rate of adoption of the application may be attributed to the fact that the elite farmers who were selected, sensitized and then trained in the use of PlantVillage Nuru did not disseminate the knowledge gained from the training to their grassroots communities. This could be explained by the lack of technical and financial resources available to these elite farmers, hindering their ability to achieve a meaningful outreach. Additionally, the recent introduction of the application in the study area may have contributed to its low adoption rate. This is consistent with the findings of [27], who demonstrated that the introduction of a new technology requires a considerable amount of time for it to be fully appropriated and widely disseminated on a large scale. Consequently, in order to improve the adoption rate of the PlantVillage Nuru application, it is necessary to decentralize awareness-raising and training efforts to the community level. These initiatives should highlight the economic incentives offered by the Nuru application, such as yield gains and increased net margins for cassava farmers. Future research should focus on quantifying the impact of Nuru application adoption to effectively communicate these benefits. This would enable a large number of sensitized and trained farmers to be reached. Similarly, given that the majority of farmers are frequently in contact with extension services, it is important to establish partnerships with these services and with non-governmental organizations involved in farm advisory services. This collaboration should facilitate the integration of the use of Plant Village Nuru application into agricultural training programs, thereby reaching a larger number of farmers. Furthermore, local or community radio stations are among the suitable means of disseminating information about the Nuru application, particularly in rural areas where internet access is limited.

4.2. Analysis of the Determinants of the Adoption of the PlantVillage Nuru Application

4.2.1. Participation in Training and Awareness-Raising Sessions

The participation of farmers in training and awareness-raising sessions has a positive influence on their decisions regarding the adoption of the PlantVillage Nuru application (Tables 4 and 5). Farmers who adopt PlantVillage Nuru in the management of cassava viral diseases have attended at least one training or awareness-raising session. The works of prior authors [12,28,29] have demonstrated that there is a strong correlation between farmer awareness and the adoption of agricultural technologies following dissemination. Consequently, farmer awareness and training play a pivotal role in the adoption of agricultural technologies. Such initiatives allow farmers to become aware of the existence of technologies and to understand the benefits of these technologies, how to use them effectively and how they can improve their agricultural practices and livelihoods. Training and awareness are therefore key means to facilitate the adoption and effective use of agricultural technologies.

4.2.2. Possession of an Android Smartphone

This study shows that the use of the PlantVillage Nuru application is significantly linked to the farmer's possession of an Android-type mobile phone. Most farmers do not initially own an Android phone due to limited financial resources for some and inability to read and understand French and English for others. Similarly, some farmers find the operation of the Android phone quite complicated and are therefore not interested in it. Only farmers who own this type of phone and have an acceptable level of French or English, in the case of Benin, will be able to use this application. These results are in line with those of prior authors [30,31], who have also demonstrated that the main constraints on the adoption of agricultural applications include the ownership of smartphones and mastery of their use.

4.2.3. Education Level

This study has revealed a strong correlation between the level of education (secondary level) and the use of the PlantVillage Nuru application (Tables 4 and 5). This finding is supported by the fact that the application requires the farmer to be able to read and understand one of the languages used (French or English, for example). It can be reasonably assumed that an educated farmer will have a better understanding of this technology and the key concepts of its use [13,17,31,32]. Nevertheless, it was observed in Ref. [33] that individuals with no formal education are still able to perform basic operations with their mobile phone, such as making phone calls. In contrast, in the case of mobile agricultural applications, which offer a greater range of functions, a higher level of instruction is required. Consequently, it can be concluded that farmers with a high level of education are better qualified and more likely to adopt this type of application.

4.2.4. Knowledge About CMD

This study indicates that a good knowledge of cassava mosaic disease (CMD) has a positive influence on the adoption of the PlantVillage Nuru application. This observation could be explained by the fact that prior knowledge of CMD allows farmers to recognize the symptoms of the disease when they see them in their fields and to use the application to confirm their suspicions and obtain advice on its management. This enables them to save time through the rapid and accurate identification of diseases, thus allowing them to focus on other crucial agricultural tasks. Furthermore, farmers with a deeper understanding of the subject matter can utilize the Nuru application as a training tool for less experienced workers or farmers on their farms, thereby enhancing overall farm productivity. The authors of Ref. [12] assert that when farmers lack awareness of the disease affecting their crops or possess insufficient knowledge of it, they are unlikely to adopt a solution in the form of a developed technology and may be indifferent to this technology. A profound comprehension of the disease should facilitate farmers to comprehend the recommendations of the application and make informed decisions about the management of their crops. In general, the lack of knowledge among farmers regarding plant diseases and their causes represents a significant obstacle to the implementation of management strategies [34,35]. Consequently, an enhanced understanding of CMD among farmers not only encourages the uptake of the PlantVillage Nuru application but also facilitates more effective disease management in their fields, which can ultimately lead to enhanced productivity and augmented food security in farming communities. Furthermore, although Nuru is designed to assist those with limited knowledge, its features also offer considerable benefits to more experienced farmers.

4.2.5. Crop Association

This study demonstrates a positive correlation between the practice of intercropping and the adoption of the PlantVillage Nuru application by farmers (Tables 4 and 5). Intercropping, which involves the cultivation of multiple plant species on the same plot, is an effective strategy to promote a diversified cropping system, by creating complementary relationships among the cultivated crops [36]. This practice is commonly observed in cassava cropping systems [5,37,38]. Some crops associated with cassava could serve as host plants for the vectors of the CMD virus, thereby influencing the severity of the disease in cassava fields [39]. In this context, the PlantVillage Nuru application can assist farmers practicing intercropping to accurately identify the disease affecting their cassava plants and provide recommendations for its management. When the associated crops are compatible, they can have an impact on CMD by significantly reducing (by 10 to 40%) the incidence of the disease in diversified plots [40–42]. The PlantVillage Nuru application can also help farmers select the most appropriate associated crops to manage CMD. This application represents a valuable tool for addressing the diversity and complexity of challenges faced by farmers in their fields. It can lead to more effective disease management by providing real-time field diagnosis, advising on phytosanitation practices such as planting virus-free material and using resistant varieties, helping farmers monitor the phytosanitary status of their fields and select healthy cuttings for planting, and offering general agricultural advice on best practices for cassava cultivation. Additionally, it promotes more rational use of agricultural lands and improved productivity. However, it is important to note that managing multiple crops in the same field can sometimes prove complex. The authors of Ref. [5] propose that monoculture of cassava would help to maintain fields free of weeds and other crops that may act as reservoirs for viruses responsible for CMD.

5. Conclusions

This study provides a comprehensive analysis of the key determinants influencing the adoption of the PlantVillage Nuru application among cassava farmers in Benin. Despite the potential benefits of this technology, the adoption rate remains relatively low, underscoring the need for targeted interventions to enhance adoption. The econometric analysis has identified several significant factors that influence the adoption of the PlantVillage Nuru application. These include participation in training and awareness sessions on cassava mosaic disease (CMD), ownership of an Android mobile device, knowledge of CMD, level of education and the practice of intercropping. These findings indicate the critical role of education and awareness in promoting the use of the PlantVillage Nuru application. Farmers who are well-informed about CMD and understand the benefits of the application are more likely to adopt it. Consequently, there is a pressing need to intensify efforts to educate farmers about CMD and the potential benefits of using the PlantVillage Nuru application.

In light of these findings, it is recommended that a comprehensive training and awareness programme on CMD and the use of the PlantVillage Nuru application be developed and implemented. This programme should be designed to reach a wide range of farmers and should be delivered in local languages to ensure understanding. The implementation of these recommendations will facilitate the adoption of the PlantVillage Nuru application, thereby enhancing disease management, crop yields and food security in Benin. This study contributes to the growing body of literature on the adoption of agricultural technologies and offers practical insights for policymakers, agricultural extension services and technology developers.

Author Contributions: Conceptualization, D.K.D.A., E.M.F.W.S.-C. and J.A.Y.; Methodology, D.K.D.A., E.M.F.W.S.-C., J.A.Y. and M.Z.-T.; Software, D.K.D.A.; Validation, E.M.F.W.S.-C., J.A.Y. and J.A.H.; Formal analysis, D.K.D.A.; Investigation, D.K.D.A., J.A.H. and S.S.H.; Data curation, D.K.D.A.; Writing—original draft, D.K.D.A.; Writing—review & editing, E.M.F.W.S.-C., J.A.Y., M.Z.-T., J.A.H. and S.S.H.; Visualization, J.A.Y., J.A.H. and S.S.H.; Supervision, E.M.F.W.S.-C., J.A.Y., M.Z.-T., J.S.P. and C.A.; Project administration, J.S.P. and C.A.; Funding acquisition, J.S.P. and C.A. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported, in whole or in part, by the European Union (EU) through the Biorisks project executed by the Regional Center of Excellence for Transboundary Plant Pathogens, Central and West African Virus Epidemiology (WAVE) and the Conseil Ouest et Centre Africain pour la Recherche et le Développement Agricoles (CORAF), grant number: CORAF N°: SC001_MC001 _UE-WAVE CRIS n° FOOD 2019/411-531, the Bill and Melinda Gates Foundation and the United Kingdom Foreign, Commonwealth and Development Office (FCDO; INV-002969; grant no. OPP1212988) through a subgrant from the Université Félix Houphouët-Boigny (UFHB) to Université Abomey-Calavi, Benin. Under the grant conditions of the Foundation, a Creative Commons Attribution 4.0 Generic License has already been assigned to the author-accepted manuscript version that might arise from this submission.

Institutional Review Board Statement: Not applicable.

Data Availability Statement: The data supporting the reported results are accessible upon request from the Central Laboratory of Plant Biotechnology and Crop Improvement (LCBVAP), University of Abomey-Calavi (UAC), Benin Republic. For inquiries, please contact Professor Corneille AHANHANZO via email at corneille.ahanhanzo@wave-center.org and Dèwanou Kant David AHOYA, via email at davidahoya13@gmail.com. Access to these data will be provided free of charge after its publication in the journal "Agriculture" following MDPI Research Data Policies.

Acknowledgments: Our sincere gratitude extends to the diligent extension agents and enumerators who meticulously collected high-quality and informative data, thereby contributing to the existing body of knowledge. We would also like to express our heartfelt thanks to the dedicated farmers for generously sharing their valuable insights and time. Lastly, we would like to give special recognition to Fidèle Tiendrébéogo for enhancing the manuscript and to Durand Lokossou for their invaluable assistance in mastering STATA 17.

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

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