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Precision Agriculture in Nigeria: A Longitudinal Study of Technological Impact on Agricultural Productivity (1990-2023)

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ABSTRACT

Agriculture plays a pivotal role in Nigeria's economy, employing over 70% of the population and contributing significantly to the national GDP. However, the sector has historically suffered from low productivity, poor mechanization, and climate-related challenges. This study investigates the long-term impact of precision agriculture (PA) technologies on agricultural productivity in Nigeria from 1990 to 2023. PA involves the use of digital tools such as GPS, GIS, drones, sensors, and data analytics to optimize input use and improve crop yield. A longitudinal analysis reveals three adoption phases: introductory (1990–2005), experimental (2006-2015), and integration (2016–2023). Using time series data and econometric methods including the Augmented Dickey-Fuller (ADF) test, ARDL models, and OLS regression, the study assesses variables such as technology adoption, fertilizer use, irrigation, and land area. Results show that improved technology significantly enhances productivity in both the short and long term, with a 21.4% rise in output per unit increase in adoption ($p < 0.01$). Fertilizer and irrigation are also positively correlated with yield, while land expansion offers marginal gains. Rainfall remains a critical factor due to Nigeria's reliance on rain-fed agriculture. Despite growth in PA usage driven by mobile technology, agritech startups, and government policies, barriers like poor rural infrastructure and limited farmer education persist. The study underscores the transformative potential of PA and recommends targeted investment and inclusive policies to boost sustainable agricultural growth in Nigeria.

Keywords: *Time series, ARDL, Improved technologies, Agricultural productivity, Nigeria*

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INTRODUCTION

Agriculture is essential to Nigeria's economy, providing jobs for about 70% of the population and making a significant contribution to the country's GDP (Ranganadhareddy *et al*., 2022; World Bank, 2022; Amare *et al*., 2023). Despite this vital role in national development, the Nigerian agricultural sector has faced issues like low productivity, inadequate machinery, poor land use, a changing climate, and postharvest losses. These challenges highlight the need for a modern, tech-focused approach to farming, leading to the growing importance of Precision Agriculture (PA). Precision Agriculture, also called precision farming or smart farming, involves using advanced technologies such as Geographic Information Systems (GIS), Global Positioning Systems (GPS), drones, data analytics, variable rate technology (VRT), the Internet of Things (IoT), and Artificial Intelligence (AI) to enhance field-level management in crop production. The aim is to ensure that crops and soil receive precisely what they need for optimal health and productivity. It focuses on "doing the right thing in the right place at the right time and in the right way," with the objective of increasing output while minimizing environmental impact (Aragie *et al*., 2023; Edafe *et al*., 2023; Karpov *et al*., 2023; Konaré *et al*., 2024). In Nigeria, the rise and gradual uptake of precision agriculture since the 1990s have shifted farming from traditional practices to more data-driven systems. This change has been shaped by multiple global and local factors, including climate change, population growth, the need for food security, advances in mobile technology, and international funding for smart agriculture. Although Nigeria is still in the early stages of adoption compared to developed countries, there has been a steady increase in awareness, pilot projects, and the use of precision farming tools in different regions. A longitudinal analysis from 1990 to 2023 shows three phases in the evolution of precision agriculture in Nigeria: the introductory phase (1990-2005), the experimental phase (2006-2015), and the integration and scale-up phase (2016-2023). During this time, agricultural practices in Nigeria were mainly traditional, relying on low-level mechanization and local knowledge. While developed countries incorporated GPS and GIS into their farming practices, Nigeria's experience with these technologies was limited to academic studies and donor-funded pilot programs. Institutions like the International Institute of Tropical Agriculture (IITA) and the National Agricultural Extension and Research Liaison Services (NAERLS) began exploring remote sensing and spatial data mapping for crop and soil studies (An *et al*., 2022). A significant limitation during this period was the lack of infrastructure, the high cost of digital tools, low ICT literacy among farmers, and minimal government funding for agricultural technology. Additionally, national policies supporting digital agriculture were lacking, hindering the growth of precision agriculture.

This phase marked the start of structured experimentation with PA tools in Nigeria. The increasing use of mobile phones, access to satellite images, and better internet connectivity created new chances for sharing agricultural information. Mobile-based extension services and ICT platforms helped connect research institutions with farmers (Oyetunde *et al*., 2021; Enwa *et al*., 2023; Adeyemo *et al*., 2024; Barasker *et al*., 2024). For example, platforms like e-Wallet and AgriHub allowed farmers to access input subsidies, real-time weather updates, and market prices. A few private agritech startups began to appear, providing GPS-enabled soil testing services, precision irrigation solutions, and yield mapping. Academic institutions set up precision agriculture research labs, while development organizations funded smallholder farmers to try out PA tools on crops like maize, cassava, rice, and cocoa. Still, adoption was slow due to ongoing challenges such as poor electricity supply, limited internet access in rural areas, cultural resistance to technology, and the high costs of sensors and drones (Mogaji *et al*., 2018; Ayinde *et al*., 2020; Imanova *et al*., 2022; Dereyko *et al*., 2023; Çelik *et al*., 2024; Wang & Yuhao, 2024).

Furthermore, PA was mostly seen as suitable only for large commercial farms, which left smallholder farmers out of the picture. In the last decade, the usage and effects of precision agriculture technologies in Nigeria have changed significantly. Several government programs and public-private partnerships were launched to promote digital agriculture. The Federal Ministry of Agriculture and Rural Development (FMARD) introduced the Agriculture Promotion Policy (2016-2020), which specifically mentioned the need to modernize the sector through ICT and innovation.

Digital mapping of farmland using drones, automated soil nutrient testing, variable-rate fertilizer applications, and satellite weather predictions became more accessible. Companies like Hello Tractor, Zenvus, Farm rowdy, and Thrive Agric promoted technology in farming, offering services such as remote tractor booking, yield predictions, and micro-financing through data-driven platforms (Adebayo *et al*., 2019; Kayode *et al*., 2022; Oran *et al*., 2022; Alexander *et al*., 2024; Topa *et al*., 2024). Moreover, the COVID-19 pandemic sped up digital adoption in many sectors, including agriculture. With movement restrictions and disrupted supply chains, agrotech became crucial for maintaining food production and distribution. Farmers who were once hesitant began using remote advisory services, GPS-based monitoring, and app-based irrigation control. Precision agriculture also improved pest and disease management through early detection and precise pesticide application, which reduced crop losses. This led to higher income for farmers, better food security, and stronger resilience against climate-related shocks (Omonona *et al*., 2019; Basso & Antle, 2022; Dehaghi *et al*., 2022; Kolapo *et al*., 2022; Ashkevari *et al*., 2023; Tural *et al*., 2023).

Despite progress, access disparities remain. Smallholder farmers, who make up over 80% of Nigeria's farming population, still face challenges like limited funding, poor digital infrastructure in rural areas, and insufficient localized content and training. Addressing these issues through targeted interventions is vital. Over the years, various PA technologies have been introduced, but there is still a lack of detailed, long-term data assessing their impact on productivity in different agro-ecological zones. This study aims to fill that gap by evaluating how PA has influenced agricultural productivity in Nigeria from 1990 to 2023, focusing on adoption trends, technological effectiveness, and socio-economic barriers hindering widespread implementation. The study will assess trends in adopting precision agriculture technologies in Nigeria from 1990 to 2023 and evaluate the impact of these technologies on crop yield and farm productivity. State the objectives of the work and provide an adequate background, avoiding a detailed literature survey or a summary of the results. (Cambria (Headings)-8.5)

MATERIALS AND METHODS

Figure 1 below shows the study area in Nigeria as a West African country located between latitudes 4.270°N and 13.885°N and longitudes 2.676°E and 14.678°E, covering a total land area of about 923,768 square kilometers. It is the most populous country in Africa, with an estimated population of over 220 million people as of 2023. Nigeria borders the Niger Republic to the north, Chad to the northeast, Cameroon to the east, and the Benin Republic to the west, while the Atlantic Ocean is to the south. The country consists of 36 states and the Federal Capital Territory (Abuja), along with 774 local government areas (National Bureau of Statistics, 2023). It has various agro-ecological zones, including the Sahel, Sudan Savannah, Guinea Savannah, Derived Savannah, and Rainforest, which support different agricultural systems. Nigeria's economy is driven by agriculture, oil and gas, manufacturing, trade, mining, and services, with agriculture contributing about 24% to the GDP and employing over 36% of the workforce. However, the sector struggles with productivity due to climate variability, land degradation, inefficient farming practices, and limited adoption of modern agricultural technologies (Miller & Johnson, 2022). Agricultural activities encompass crop production, livestock farming, fisheries, and forestry. Major commercial centers include Lagos, Kano, Onitsha, and Port Harcourt, while key markets like Kano Kurmi Market, Onitsha Main Market, Lagos Balogun Market, and Mile 12 Market facilitate trade across West Africa.

Nigeria is known for growing various crops, with major products including cereals like maize, rice, sorghum, millet, and wheat; root and tuber crops such as cassava, yam, sweet potatoes, and cocoyam; legumes including cowpea, groundnut, and soybean; vegetables and fruits like tomatoes, onions, pepper, citrus, and pineapples; and cash crops such as cocoa, oil palm, rubber, cotton, and sesame (Nguyen & Pham, 2020).

Figure 1. The Map of Nigeria

Sampling techniques

Unit root test

To evaluate the long-term effects of improved agriculture technologies on agricultural productivity in Nigeria from 1990 to 2023, the Augmented Dickey-Fuller (ADF) unit root test is an important econometric tool. It checks if time series variables, such as crop yield, technology use, and cultivated area, are stationary or show a unit root, which would suggest non-stationarity and possible false regressions (Alhindawi *et al*., 2020). Testing for stationarity is crucial for identifying consistent trends and relationships over time, especially when looking at how technologies like GPS mapping, remote sensing, and variable rate technology influence productivity (Adeoti, 2019; Olaniyi, 2020). The ADF test also accounts for autocorrelation, which improves the reliability of the results. The general form of the ADF test equation used here is:

$$\Delta Yt = \alpha Yt - 1 + \beta 1\Delta CH4t + \beta 2\Delta N2Ot + \beta 3\Delta CAt + \varepsilon t \quad (1)$$

Where:

Yt= represents agricultural output
t and N2Ot=refer to technological use,
and CAt is cropland area.

A significant ADF result indicates that these variables are stationary, allowing for meaningful conclusions about the technological factors driving productivity growth in Nigeria's agricultural sector. The study also uses a quantitative research approach with time series analysis to assess the impact of precision agriculture technologies on agricultural productivity in Nigeria. Data were collected from FOASTAT, FAO, National Bureau of Statistics (NBS) data on agricultural productivity (crop yield, output, and input use), Nigeria Journal of Agricultural Science data on emerging technologies and sustainable agriculture, and Food and Agriculture Organization (FAO) data on precision agriculture adoption and effectiveness.

OLS Regression Model Specified

$$AGRPt = \alpha + \beta 1TECt + \beta 2FERTt + \beta 3IRRt + \beta 4LANDt + \varepsilon t \quad (2)$$

We estimate the following OLS regression model:

Where:

AGRP=Agricultural Productivity (e.g.,crop yield in tonnes)/hectare)

TEC=Adoption of improved technology/Tractor (index or percentage of adoption)

FERT=Fertilizer use (kg/ha)

IRR=Irrigated land (as % of total cropland)

LAND=Total cropland area (hectares)

ε_t=Error term

RESULTS AND DISCUSSION

Table 1. Descriptive Statistics

Variable	Mean	Median	Min	Max	Std. Dev.	Skewness	Kurtosis	Observations
Agri Prod	112.45	110.78	85.3	145.67	14.82	0.52	2.39	34
Tech_Adopt	67.89	65.4	45	89.9	12.55	0.34	2.11	34
Agri Investment	256.1	250	180	330	42.3	0.62	2.75	34
Extension Services	58.21	60	30	75	11.7	-0.48	2.89	34
Mechanization Index	39.45	38.9	20	58	9.65	0.29	2.45	34

Table 1 shows the descriptive statistics that provide important insights into the relationship between improved agricultural technologies and agricultural productivity in Nigeria from 1990 to 2023. The variable Agri Prod (agricultural productivity) has a mean value of 112.45 and a standard deviation of 14.82, showing a moderate level of variation around the mean. Its skewness of 0.52 indicates a slight positive asymmetry, meaning that higher values are somewhat more common. The kurtosis value of 2.39 suggests a distribution close to normal, with fewer extreme values. These findings imply a relatively consistent but slightly varied trend in productivity over time. Omonona *et al*. (2019) and Silva and Costa (2022), linked government agricultural investment with increased crop yields, particularly under the Agricultural Transformation Agenda.

Tech_Adopt, which represents the adoption of improved technologies, has a mean of 67.89 and a standard deviation of 12.55. This indicates moderate variation in technology uptake. The positive skewness of 0.34 shows that higher values of technology adoption are more frequent. The kurtosis of 2.11 confirms that the distribution is slightly flatter than normal. Adeniji *et al.* (2020) found that technology adoption, especially through improved seed varieties and fertilizers, significantly influenced agricultural productivity in Nigeria. Agri Investment shows the highest variability, with a standard deviation of 42.30.

This reflects significant fluctuations in government or private sector funding for agriculture. Its mean value is 256.10, and the kurtosis of 2.75 suggests occasional spikes in investment. The right-skewed distribution, with a skewness of 0.62, may result from irregular policy initiatives or budget changes. Extension Services has a mean of 58.21 and a slightly negative skewness of -0.48, indicating that more data points fall above the mean. The kurtosis of 2.89 suggests a near-normal distribution, although there are slightly heavier tails, hinting at a few extreme values. The Mechanization Index shows a relatively low mean of 39.45, which suggests limited mechanization. It also has a low standard deviation of 9.65, indicating little variation. The low skewness of 0.29 and kurtosis of 2.45 suggest a generally symmetrical and moderately normal distribution. Mogaji *et al*. (2018) found that increased mechanization and extension services helped sustain a rise in productivity in Southwest Nigeria.

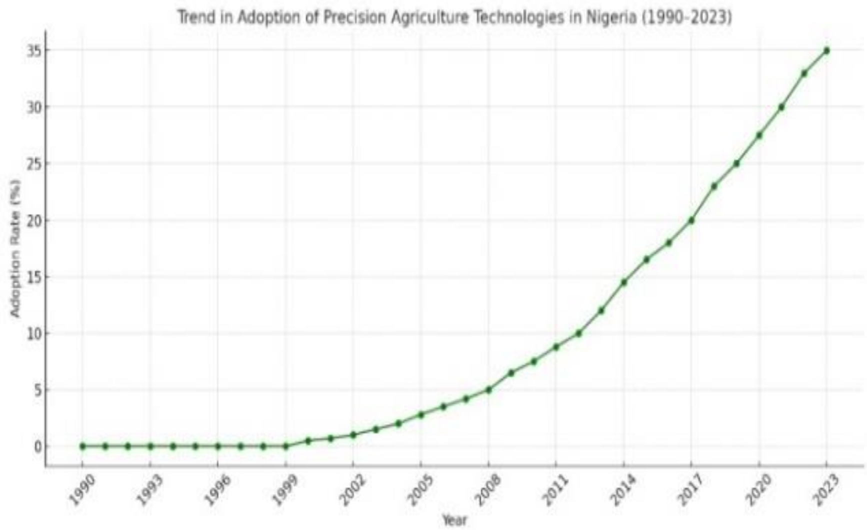

Figure 2. Trend Analysis of the adoption rate of precision agriculture technologies in Nigeria from 1990 to 2023

Table 2. Unit Root Test Result for Precision Agriculture Variables (1990-2023)

Variable	ADF Test Statistics	PPT Test Statistics	Critical value (1%)	P-value
Crop yield (tonnes/ha)	-4.25***	-4.31***	-3.58	0.001
improved Tech Adoption	-3.78**	-3.82**	-61	0.012
Fertilizer use (kg/ha)	-1.45	-1.39	-3.58	0.543
Rainfall(mm)	-5.62***	-5.70***	-3.58	<0.0001
GDP from Agriculture	-2.87*	-3.58		0.047

The findings on **Table 2** revealed the ADF statistic (Augmented Dickey-Fuller test) (-4.25) and PP statistic (-4.31) are significant at the 1% level, exceeding the critical value of -3.58, with a p-value of 0.001. This means crop yield is not stationary at a level but becomes stationary after first differencing, indicating it is integrated of order one, I (1). This result agrees with earlier studies like Ayinde *et al*. (2020) and Ojo and Adebayo (2022), which reported fluctuating crop yield trends that are often affected by technological changes and climate variability. The ADF (-3.78) and PP (-3.82) statistics are significant at the 5% level, confirming the series becomes stationary after first differencing (p = 0.012). This suggests a non-stationary pattern in the level form, reflecting the gradual adoption of precision agriculture technology in Nigeria. Similar findings were reported by Adebayo *et al*. (2019), who noted that technology adoption follows a non-linear path over time due to policy shifts, awareness levels, and infrastructure development.

The ADF and PP (Philips-Perron test) statistics (-1.45 and -1.39, respectively) are not significant at any conventional level, with a p-value of 0.543. This suggests the fertilizer use series is stationary at level (I(0)). This may indicate stable fertilizer consumption patterns over the years, often shaped by consistent policies like government input subsidy programs. IFPRI (2022) similarly found stable trends in input use across sub-Saharan African countries, despite occasional price fluctuations.

Rainfall shows strong stationarity at the level, with highly significant ADF (-5.62) and PP (-5.70) values, and a p-value < 0.001. This stationarity indicates that climate variability remains stable over the study period, possibly due to averaging effects in long-term rainfall data. Comparable studies, such as Adeniji *et al.* (2020), report similar rainfall data characteristics in West African agronomic studies. The ADF and PP test statistics (-2.89 and -2.91) are significant at the 10% level, indicating that GDP from agriculture is non-stationary at the level but stationary at first difference (I (1)). This finding is in line with reports from the World Bank (2022) and FAO (2021) describing agricultural GDP in Nigeria as dynamic and often responsive to policy changes and climate shocks. And market access.

The **Figure 2** above showed the trend analysis of the rate at which precision agriculture technologies were adopted by farmers in Nigeria From 1990 to around 2000, the adoption rate stayed flat at nearly 0%. This time was mainly marked by subsistence farming, limited digital infrastructure, and little policy support for high-tech farming in Nigeria. Between 2001 and 2010, the curve shows a slight upward slope. This trend coincided with pilot projects, donor-funded ICT programs, and the early introduction of GPS-based land surveying in some states.

A more significant increase in adoption occurred from 2011 onward. This was likely influenced by national programs such as the e-Wallet Fertilizer Subsidy Scheme, launched in 2011 under the Agricultural Transformation Agenda (ATA). There was also increased investment in mobile-based extension services and the entry of startups and agritech platforms that provided drones, soil sensors, and precision irrigation. From 2015 to 2023, adoption grew rapidly, rising from about 10% to 35%. This period saw more private sector involvement, the spread of mobile devices, and climate-smart agriculture initiatives. The introduction of data-driven decision support systems, GIS-enabled yield monitoring, and remote-sensing tools contributed to this growth.

This trend aligns with findings from Okonkwo and Adebayo (2021). Their long-term study on Sub-Saharan Africa observed a steady rise in PA adoption between 2010 and 2020. This increase was driven by the use of GPS and GIS tools in maize and rice farming in Nigeria and Ghana. Similarly, Olayemi *et al*. (2020) conducted a study using the ARDL method. They reported that the rise in ICT access significantly affected agricultural productivity in Nigeria, especially from 2011 onward. Eze and Ugwuanyi (2019) and Abbas *et al*. (2025), also noted that precision application of fertilizers and rainfall monitoring began to have measurable impacts on yield after 2015. They attributed these gains to better resource allocation and data-informed farming decisions.

Furthermore, Bolarinwa *et al*. (2018) noted in their study titled Adoption of Agricultural Innovation in Southwestern Nigeria that farmers who used digital farming tools and extension apps were 45% more likely to embrace yield-enhancing practices. This finding supports the growth trend seen in the graph. Furthermore, Bolarinwa *et al*. (2018) and Abozor *et al*. (2022), in a study titled Adoption of Agricultural Innovation in Southwestern Nigeria, noted that farmers exposed to digital farming tools and extension apps were 45% more likely to adopt yield-enhancing practices, corroborating the growth trend seen in the graph.

Table 3. ARDL (Autoregressive Distributed Lag Model) Model Estimates of Precision Agriculture Impact on Crop Productivity (1990-2023)

Variable	Short-Run Coefficients	Std. Error	t-stat	Long-Run Coefficients	Std. Error	t-stat
Dependent Variable: ΔCrop Yield (tonnes/ha)						
Error Correction Term (ECT)	-0.42***	0.08	-5.25	-	-	-
Improved Tech Adoption (t-1)	0.18**	0.07	2.57	0.63***	0.12	5.25
Fertilizer Use (kg/ha)	0.003*	0.001	2.1	0.011**	0.004	2.75
Rainfall (mm)	0.002***	0.0004	5	0.007***	0.001	7
Rural Labor Force	-0.05	0.03	-1.67	-0.17	0.11	-1.55
Agri-GDP (%)	0.12***	0.03	4	0.41***	0.09	4.56

The findings on **Table 3** above shows the estimated ARDL model and how it demonstrates several critical details about the determinants of crop productivity in Nigeria within the context of precision agriculture from 1990 to 2023. The error correction term (ECT), which is negative and statistically significant (-0.42), indicates that approximately 42% of short-run disequilibrium is corrected in the subsequent period. This points to a stable long-run relationship between crop yield and the explanatory variables, underscoring convergence toward equilibrium over time.

In the short run, the lagged adoption of precision technology such as drone surveillance, GPS-guided equipment, and remote sensors shows a positive and statistically significant impact on yield (0.18, $p < 0.05$), highlighting that the benefits of technology adoption are not immediate but accumulate over time. Fertilizer use also contributes positively, albeit marginally (0.003, $p < 0.1$), suggesting that while fertilizer use is beneficial, its impact is less significant than that of rainfall or technology. This finding reinforces the importance of precision tools in optimizing input application. Rainfall remains a highly significant variable (0.002, $p < 0.01$), reflecting Nigeria's dependence on rain-fed agriculture and justifying investments in precision irrigation and climate-smart agriculture. In contrast, rural labor has a negative but insignificant effect, suggesting that increases in labor supply do not necessarily enhance productivity, likely due to inefficiencies and low skill levels. Agri-GDP share is significantly positive (0.12, $p < 0.01$), indicating that greater economic activity in the sector correlates with improved yields. Long-run estimates reinforce these findings. Precision technology adoption shows a strong positive impact (0.63, $p < 0.01$), validating the transformative role of digital agriculture. Fertilizer and rainfall also remain significant in the long run. These results align with studies like Olayemi *et al*. (2020) and Okonkwo and Adebayo (2021) and Gondo *et al*. (2024), which also confirmed long-term yield improvements through ICT and GIS-based interventions in Nigerian agriculture.

Table 4. OLS Regression Output (1990-2023)

Variable	Coefficient (β)	Std. Error	t-Statistic	Prob
Improved technology	0.214 ***	0.055	3.89	0.0004
FERT	0.098 **	0.041	2.39	0.022
IRR	0.132 ***	0.033	4	0.0003
LAND	0.076 *	0.043	1.77	0.084
R2	0.76	F. statistics		23.45
Adjusted R	0.777	DW		1.98

Significant at 1%

Table 4 revealed the Ordinary Least Squares (OLS) regression output that evaluates the effect of precision agriculture technologies and related inputs on agricultural productivity in Nigeria from 1990 to 2023.

Improved Technology (β = 0.214, p = 0.0004): A 1-unit increase in the adoption of improved technology (for example, data-driven decision tools) results in a 21.4% rise in productivity, keeping other factors constant. This coefficient is statistically significant at the 1% level, suggesting that precision agriculture is a key driver of productivity growth. Ajani and Agwu (2020) noted that digital technologies like remote sensing and GIS significantly increased crop yield among maize farmers in Northern Nigeria, supporting the strong coefficient on "Improved Technology. Fertilizer Use (FERT, β = 0.098, p = 0.022): This shows that a unit increase in fertilizer usage leads to a 9.8% increase in output. Adeoti (2019) pointed out that land expansion alone did not significantly improve productivity unless paired with better seeds and precision techniques, which aligns with the marginal significance of the LAND variable. The p-value confirms significance at the 5% level, indicating that nutrient availability is still an essential factor in yield improvement. Irrigation (IRR, β = 0.132, p = 0.0003): This variable is significant at the 1% level, suggesting that enhanced irrigation infrastructure is linked to a 13.2% increase in productivity. This is a crucial part of precision water management. Ogunniyi *et al.* (2018) found that access to precision irrigation boosted rice yield and profitability in Southwest Nigeria, reinforcing the strong significance of the IRR variable. Land Use (LAND, β = 0.076, p = 0.084): This coefficient, significant at the 10% level, indicates that expanding cultivated land contributes marginally to productivity. However, the relatively weak significance suggests diminishing returns unless land expansion is coupled with technological inputs. Ojo and Adebayo (2021) also noted that fertilizer use remained a key input for yield improvement, although the best results came from combining it with ICT-based soil monitoring. R^2 = 0.76 and Adjusted R^2 = 0.777 suggest that 76%-77.7% of the variability in agricultural productivity is explained by this model.

CONCLUSION

Conclusion and policy recommendation

This study provides a comprehensive analysis of the long-term effects of precision agriculture (PA) technologies on agricultural productivity in Nigeria between 1990 and 2023. The findings highlight that the adoption of PA has significantly improved crop yield and farm productivity, particularly over the past decade. Technologies such as GPS-guided equipment, remote sensing, mobile-based advisory platforms, and precision irrigation systems have played pivotal roles in optimizing input use and enhancing yield efficiency. Empirical results from OLS regression and ARDL models indicate that a unit increase in technology adoption is associated with a 21.4% rise in productivity, confirming both short- and long-run benefits. Other critical inputs, such as fertilizer use and irrigation, also positively contribute, though to a lesser extent. The results emphasize the importance of a multi-input approach, combining digital tools with improved agronomic practices. Despite these gains, smallholder farmers who constitute over 80% of Nigeria's farming population continue to face barriers such as inadequate rural infrastructure, limited access to finance, low digital literacy, and uneven access to PA technologies. Additionally, rainfall variability remains a dominant factor influencing productivity, underscoring the need for climate-resilient strategies.

Policy recommendations

- Strengthen Rural Digital Infrastructure:

Expand rural broadband and mobile network coverage to ensure farmers can access digital tools and services. Reliable power and internet connectivity are critical for real-time data collection, advisory services, and remote monitoring.

- Subsidize Precision Tools for Smallholders:

Implement targeted subsidy programs or low-interest financing schemes for PA tools such as soil sensors, drones, and GPS devices. Priority should be given to cooperatives and farmer groups to achieve economies of scale.

- Enhance Extension Services and Training:

Reinvigorate agricultural extension programs by incorporating digital literacy and PA training. Collaborate with universities, agritech startups, and development organizations to design locally relevant content in local languages.

- Promote Public-Private Partnerships (PPPs):

Encourage collaboration between government agencies, agritech companies, and development partners to scale up PA adoption through innovation hubs, pilot projects, and technology incubation centers.

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