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The Impacts of Precision Technologies on Cropping System in Developing Countries: A Case Study for Nigeria

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Abstract

Global agricultural systems are undergoing rapid transformation due to increasing food demand. Precision agriculture technologies such as GPS-guided machines, drone and satellite imagery, and IoT-based sensors have emerged as key solutions to optimize farming practices. These technologies increase crop yields, improve resource use efficiency, and support economic profitability. Thanks to these technologies, all processes are data-driven, facilitating decision-making. When all these features are considered together, it is obvious that they also promote environmental sustainability. However, access to these technologies is not the same in every country. Demonstrating the status of access to these technologies, especially in developing countries, will contribute significantly to studies on food security around the world. This review examines the impact of precision agriculture technologies on modern cropping systems, focusing on ways to provide precise control over water, fertilizer, and pesticides, thereby minimizing environmental impacts and input waste. The article also discusses the challenges that smallholder farmers face in adopting precision agriculture technologies, such as high initial costs and limited technological expertise. Recommendations are made to increase the accessibility of precision agriculture technologies through government funding, educational initiatives, and infrastructure improvements. Addressing these barriers is critical to the global adoption of precision agriculture.

Key Words: *Precision agriculture technologies1, Yield optimization2, Resource efficiency3, Sustainability3, GPS-guided machinery5*

Introduction

The agricultural sector is central in the global economy; mainly in the developing countries, it forms part of the economic bedrock. Nevertheless, these countries have various problems in the agricultural sector, such as food shortages, weak farmers' markets, inadequate infrastructure, and adaptive outcomes of climate change (Connolly-Boutin and Smit, 2015). With regard to the agricultural sector, the obstacles to development in the developing regions, including Nigeria, include factors such as low productivity and improved technology and techniques (Adeyemo *et al.*, 2024). The world's population in the future is expected to rise to 9 to 10 billion, and this requirement for food production for the future population calls for enhancements in agricultural productivity of between 60% and 99% (Seelan *et al.*, 2003). Agricultural development, on the other hand, has also accelerated environmental degradation in the last few decades, making the food security mission more challenging (Roberts *et al.*, 2021). A new idea called "smart farming" uses cutting-edge information technology to increase the effectiveness and efficiency of agriculture. The most recent developments in artificial intelligence, automation, and networking allow farmers to administer exact treatments that are decided by machines with superhuman accuracy and to monitor every procedure more effectively (Unal, 2020). For maximum crop yield and quality, smart farming techniques are incorporated into nearly every stage of the growing and even marketing processes. Agriculture production may now be enhanced because of smart farming techniques (Ünal and Kızıldeniz, 2023). The challenges facing the agricultural sector, particularly in the developing world, are daunting given increasing population and climate variability, coupled by scarcer resources. Such challenges have led to the adoption of better farming practices, which replace traditional farming practices. For these complex challenges, mainstream agricultural management strategies have been complemented by precision agricultural technologies, including new sensing tools and hi-tech ICT solutions (Loudjani, 2014). Based on the doctrine of 'getting more out of more', precision agriculture, which is also referred to as precision farming or smart farming, has the potential to reduce the agriculture difficulties encountered by the developing nations. The precision agricultural technologies would increase efficiency and enhance yields with the view to eliminating food insecurity as well as making primary production more sustainable (Erickson and Fausti, 2021). Precision agriculture technologies are employed at critical phases of the agricultural growth cycle, including soil preparation, seeding, crop management, and harvesting. Moreover, precision farming technology have not only helped agricultural and fruit cultivation but have also positively impacted livestock rearing practices. Precision agriculture can be categorised into two segments: precision crop farming, which involves the utilisation of precision farming technologies to address spatial and temporal variability for enhancing crop performance and environmental quality, and precision livestock farming, which focusses on employing advanced technologies to maximise the productivity of each animal. The farmer seeks to attain improved outcomes in livestock production using this "per animal" methodology (Bucci et al., 2020). Precision crop farming and precision livestock farming are presently influenced by two predominant technical trends: big data and sophisticated analytics capabilities, alongside aerial images, feeding and milking robots, and intelligent sensors. This review article uses secondary sources to analyze various published reports and articles on precision agriculture in developing countries. It aims to provide a comprehensive overview of the topic, identify key findings, trends, and gaps, and propose effective implementation strategies. The review examines the role of precision technologies in increasing crop yields, their effects on resource efficiency, environmental benefits, economic impacts, and challenges and opportunities for future adoption in developing countries, with a particular focus on Nigeria. This paper therefore seeks to examine the adoption of precision agriculture technologies for the development of Nigeria and other developing countries. Specifically, it will draw attention to the difficulties, repercussions, constraints, and direction for applying these technologies. The study can be used as a reference for research and literature for both researchers and farmers to understand how to incorporate technology in the agricultural field.

2. Precision Agriculture Technologies

Precision agriculture has gained tremendous topicality when it comes to the discussion of the new generation of farming techniques. Through the use of GPS autonomously controlled machines, drones, satellite tools, and IOT sensors in cropping systems, information has been swiftly applied in the correct physical application of agricultural inputs with compromise to wastage or overapplication. Several precision technologies stand out in their contribution to modern cropping systems:

1. GPS-Guided Machinery: This was followed by advancements in planting, fertilizing, and spraying systems, which, with the help of GPS, can be sectioned very precisely. These tools provide a way of applying inputs in areas of need while avoiding overlaps and deficit areas. (Randal K. Taylor et al., 2013) study shows that GPS-steered systems help in increasing yields by 15% for crops like corn through consistent application of inputs.
2. Remote Sensing and Drones: Technologies such as drones and satellites allow for quick monitoring of details like crop condition, moisture levels in the soil, and much more. These insights help farmers to intervene whenever possible and probably reduce losses since all the available resources are optimally utilized.
3. IoT-Based Sensors: Some of the significant areas that relate to the use of Internet of Things (IoT) technologies include resource management, soil moisture, and environmental sensors. These sensors supply timely information in protracted intervals with respect to the soil status, hence useful in setting irrigation schedules. Using soil moisture sensors, (Lakhiar *et al.*, 2024) noted that there was a 30% saving of water used in agriculture, meaning that this was an environmental-saving method that also saved money.

2.1 Role of Precision Agriculture on Cropping Systems

Analysing these Precision agriculture technologies, they proffer several benefits to crop management i.e yield increase and better use of resources and environment. Precision yield management uses GPS-controlled application technology and related remote sensing tools for the accurate distribution of fertiliser, herbicide, or water. The distribution of required quantities at the right time benefits both crop yield and balancing the production process across various crops. Studies have shown that it leads to beneficial changes because crops require proper input to produce optimum yield (Sishodia, Ray and Singh, 2020; Lu *et al.*, 2022; Gawande *et al.*, 2023). In the field of resource utilisation and input, Precision agriculture technologies give basic information on the state of the soil, crops, and the general environment. It helps farmers in managing the resources such as water, fertilisers, and pesticides for increasing production and with least reproachable influence on the environment. Connected sensors for the specific and combined water and drone management offer precise procedures, which considerably decrease the wastage of farm resources and increase farm yield (Alahmad, Neményi and Nyéki, 2023; Rajak *et al.*, 2023). IoT technology might have a lot to offer the agricultural sector. To begin with, IoT gives farmers the ability to gather data in real time on the development and health of their crops, giving them important new information. This makes it possible to intervene proactively and make timely modifications to pest control, fertilizer application, and watering techniques. Second, by gathering comprehensive data on meteorological conditions, crop physiology, and growth patterns, IoT technologies improve the precision of yield prediction models (Kour *et al.*, 2024). As concerning the overall environmental impact, precision agriculture reduces the utilisation of agrochemicals as well as the utilisation of natural resources. Precision farming involves the application of a small amount of pesticides different from conventional methods, hence reducing pollution of soil and water. In this regard, they enable a higher or optimum eco-efficient, or least disruptive, yield per unit area relative to conventional practices (Gawande et al., 2023). These technologies have the attributes of tremendous promise for increasing the yield and also for protecting the environment in which farmers conduct their businesses.

2.2 Economic Implications

Precision agriculture technologies entail several advantages in the economic aspect. Although, implementation of precision technologies involves high initial capital investment the returns associated with investment is normally greater. The influx of precision agriculture technologies into a farming operation is often associated with gainful heights, through the possible gains from subsequent input cutbacks and upticks in product yields. For example, GPS-controlled equipment enables the farmer to minimize seeding rates or overuse fertilizers due to costs of seeds and chemicals (Lu et al., 2022; Randal et al., 2013). Likewise, Smart technologies such as IoT sensors in farming improve irrigation, thereby reducing emission of water and, thus avoiding crop failure because of inadequate water (Rajak *et al.*, 2023).

Furthermore, the precise settings in precision agriculture result from data analysis, which makes it easier to anticipate and predict the ideal time and way of doing things within a farming season (Tantalaki, Souravlas and Roumeliotis, 2019). This ability can lead to more stable income levels, and decreased monetary volatility generally attached to agriculture especially with regard to climate turbulence and unfavourable weather conditions(Monteiro, Santos and Gonçalves, 2021).

2.3 Adoption of Precision Agriculture Technologies in Developing Countries

In developing countries, there are still many problems in agriculture, including low yields, ineffective resource management, and limited accessibility to modern inputs (Bjornlund et al., 2020). Precision agricultural technologies have the potential of reforming this terrain since they provide efficiency solutions to resource poor producers, boost productivity per unit area, and reduce environmental depletion (Balafoutis *et al.*, 2017). As used in many developing countries, high costs and a lack of technical knowledge have slowed the use of precision agricultural technologies, although some countries are starting to show the possibilities of how these technologies might help (Taylor, 2023).

3. Nigeria: A Case Study

Nigeria, with its complex agricultural practices and an increasing population, continues to embrace precision agriculture technologies with the aim of increasing food production and fixing food insecurity and climate change challenges, among others (Bolaji *et al.*, 2024). A number of approaches and pilot-action have been developed to introduce established technologies such as GPS-operated equipment, drones, and IoT sensors in small-holder producers (Ajewole and Oladipo, 2010). In Nigeria, study shows that machinery that utilises GPS is already applied in enhancing the land preparation, planting, and harvesting practices. With this technology, farmers can apply fertilisers or pesticides at the nearest probability, thereby cutting costs and equal amounts of waste (Abdullahi and Sheriff, 2017). For instance, in Northern Nigeria, where commercial farming of crops like maize, wheat, and rice is practiced on a on a large scale, GPS tractors are used for correct planting spacing as well as proper distribution of seeds and fertilizers (Kamai *et al.*, 2020). This has resulted in increased crop yields and decreased input costs for those farmers who can fund such technology. Some state governments have also collaborated with private firms to finance the purchase of GPS-equipped tools for smallholder farmers (Abdullahi and Kumar, 2022). The element of drone technology that has gained significant traction with farmers in Nigerian agriculture is in crop surveillance and pest eradication (Dinrifo *et al.*, 2022). The inspectors that are incorporated into these drones are designed to generate real-time feedback on the status of the crops, the condition of the soil, and the presence of threats from pests and diseases. The gathered information assists the farmers in decision-making processes such as whether and when to irrigate, apply fertiliser, or spray for pesticides. In the southern area of Nigeria, where cocoa and cassava farming are dominant, the apparatus is being employed in surveillance of large plantations (Wossen et al., 2017). In other areas, drones help the farmers to focus on where to make the application, thus increasing productivity and at the same time reducing the usage of agrochemicals. IoT-based sensors have been adopted in various pilot projects in Nigeria concerning water management, mostly in arid regions that receive little or no rain to support irrigation (Sharpe *et al.*, 2022). These sensors measure soil moisture content and inform farmers when to water their crops cross-sectionally. This has been experienced in the northern zones of Nigeria within vegetable production of smallholder farms using IoT sensors to regulate water consumption (Akpan-Etuk, 2024). Due to over irrigation and the use of rollers, the farmers have been able to save water and have healthy crops grown. Moreover, even international organisations like the Food and Agriculture Organisation (FAO) have been funding projects that augment the use of IoT technology in projects that encourage the use of water in regions that are most affected by drought.

3.1 Increased Yield

One of the greatest advantages of using precision agricultural technologies is the gradual augmentation of crop yield in precision agriculture. Precision agricultural technologies' adoption has the potential of reducing food insecurity because in developing countries like Nigeria, small-holder farms dominate the agricultural sector. These have been evidenced by yields of between 5 and 20 percent credited to technologies like GPS auto-steered planting equipment, satellite imagery, and other complementing precision farming technologies (Randal et al., 2013). Smallholder corn farmers in Nigeria who adopted GPS agriculture on planting practices recorded better seed placement, hence better competition for nutrients and water, hence better yields (Taylor et al., 2013). Furthermore, the use of drones proves useful in the development of developing countries as well. For pesticide spraying in the rice production in Nigeria, it has been observed that drones serve the purpose without underlining the crops and enhancing the growth and yield (Hafeez *et al.*, 2023). This is well applicable, especially in the developing countries where pest attacks and unfavourable crop handling are widespread. Drones not only open possibilities for the efficient usage of pesticides but are also capable of recording the process and enabling farmers to act in a way that would increase productivity (Rejeb *et al.*, 2022). In other parts of Africa, precision agriculture technologies, in as much as they have been implemented appropriately, have resulted in increases in the yields in farming. This shows how precision agricultural technologies are not only recommendable but can also work to transform food production in areas of inadequate resources while helping farmers refine their decisions that would affect the productivity of crops.

3.2 Resource Utilization Efficiency

Enhancement of resource use productivity is the other advantage of precision agricultural technologies, especially for water-constrained and low-nutrient availability areas, common in developing nations. Smart embedded IoT soil moisture sensors and remote sensing technology enable water efficient application, and optimising the use of fertilisers greatly reduces the cost and is eco-friendly (Morchid *et al.*, 2024). Fields that grow vegetables in Nigeria utilising IoT sensors have seen the rate of watering decrease as data from the soil informs the farmers only when the watering is necessary (Douglas et al., 2016). This has led to the cutting down of water usage by 30%, meaning there is no hindrance in crop production (Rajak *et al.*, 2023). The same was the case with precision irrigation. In almond trees in California For at least 30%, water was saved while production rates were kept intact (Christian et al., 2012). It suggests that such countries facing the issue of water scarcity can adopt a policy of water conservation, a significant factor in most of the developing countries. In regions such as the northern part of Nigeria, which is faced with a scarcity of water, the use of IoT-based devices for irrigation has been identified as sustainable in the improvement of water use efficiency in agriculture (Familade et al., 2016).

In addition, there is an added advantage of precision agricultural technologies in that the application of the nutrients is made more accurate. Because several farmers in the developing countries fail to use fertilisers properly because of inadequate training, precision agricultural technologies enable costly fertiliser usage, therefore eliminating chances of nutrient leaching, which causes pollution. Numerous experiments have demonstrated the potential for the precision method of nutrient application to cut input costs by 10–25% on different farming practices, thereby increasing its profitability and efficiency (Hedley, 2015). This is especially relevant when cultivating crops and livestock in high-risk areas that impel smallholder farmers to work under severe budget constraints and with minimal capital.

3.3 Environmental Benefits

The technologies used in precision agriculture have a vital part in reducing the negative effects of concentrated agricultural activities on the environment (Getahun, Kefale and Gelaye, 2024). As these technologies allow input application to be targeted, these decreases the instances whereby fertilizers and pesticides are used in amounts that can pollute nearby ecosystems (Dehghani *et al.*, 2024). For example, (Wang *et al.*, 2019) showed that precision application of fertilizers lowered nitrogen leaching to a significant level, hence saving water bodies from pollution by nutrients. In addition, precision farming enables farmers to reduce the addition of inputs onto the soil, which has negative effects on the quality of the soil (Monteiro, Santos and Gonçalves, 2021) In the same way, agricultural Precision agriculture technologies also cause the carbon footprint of agriculture to be minimized through decreasing the usage of heavy agriculture tools and enhancing the wise utilization of natural resources in line with climate change (Sanyaolu and Sadowski, 2024).

3.4 Economic Gains

It has been realised that the adoption of precision agricultural technologies involves certain overall costs, which are nevertheless paid off in the long run by the stable advantages that are accorded to the shrewd users of these technologies of precision agriculture. A paper by (Munz and Schuele, 2022) shows that farmers who adopt precision technology use fewer inputs, produce many sellable outcomes, and therefore generate more revenues. As examples, IoT-implemented irrigation systems and GPS-navigated machinery have been proven to decrease input waste and increase operational efficiency and total yield. Comparative cross-sectional case studies indicate that it is possible to recover the initial investment cost of precision agriculture equipment in two to three years from the onset of pilot projects (Robertson et al., 2007). In the economies of developing countries such as Nigeria, the implication of precision agricultural technologies is observed in aspects of market prediction and management of agricultural businesses. Many IoT-based systems for irrigation, levee control, and GPS-based machinery have helped farmers in making intelligent decisions about the use of resources and better resistance to weather fluctuations (Familade et al., 2016).

This operational resilience results in a relatively stable income stream, which cushions the shocks that smallholder farmers generally experience due to climate change and poor physical infrastructure. Nonetheless, some studies have hypothesised that precision agricultural technologies may have positive effects on the economics of crops (Robertson et al.,2007; Munz and Schuele, 2022); nonetheless, numerous challenges persist for the application of Precision agricultural technologies, mainly because of the high costs of establishment, which are relatively high for final consumers and especially the smallholders in the developing countries. Precision agriculture technologies are capital intensive in terms of equipment, knowledge, and parts for maintenance, which most smallholder farmers cannot access. In sub-Saharan Africa, the majority of farmers practice small-scale farming, and, therefore, they are unable to obtain capital and financing sources to purchase these technologies. This limiting factor reduces viability and causes an imbalance of access, with large-gain commercial farms and resource-poor smallholders. However, the expense of using precision technologies can aggravate their applicability in smallholder farmers' context: the cost of operation. Some of these technologies depend on internet connections, especially on infrastructure, which unfortunately is not a strong point in the rural areas of developing countries. With poor investment in infrastructure and technical support, the total economic benefit of precision agricultural technologies can plateau, and this is a disadvantage to the smallholder farmers. In order to overcome the above challenges, there require subsidies assumed by governments and/or international organisations or cheaper credits to support the development of precision agricultural technologies accessible to small farmers more easily. Moreover, joint initiatives of private entities, non-governmental organisations, and the government can ease actual cost restrictions by offering such options as shared technology or cooperation, allowing smallholders to buy precision technologies collectively without bearing the full expense. However, this is not all because the long-term strategic benefits of implementing precision agricultural technologies and betterment in economic prospects are positive signs. Appropriate qualitative financial and physical inputs assist in increasing smaller-holder farmer incomes, decreasing input costs, and improving yields, thereby bringing improvements in the economics of developing countries.

3.5 Challenges to Adoption

Despite benefits achievable through Precision Agriculture Technologies, which include higher yields, effective use of resources, and profitability, their uptake is limited by several constraints, especially in the developing world. These are mainly high initial costs, technology inaccessible, and poor infrastructure that hampers smallholder farmers as well as hinders wide implementation of precision agricultural technologies. The first and perhaps one of the main challenges is that the use of Precision agricultural technologies—GPS—to control machinery, IoT sensors, and drones, among other applications, is expensive to acquire and integrate (Talaviya *et al.*, 2020). These technologies demand large capital investments, most of which smallholder farmers in developing countries cannot afford (Say *et al.*, 2017). Despite the ability to lower input costs and ramp up profitability in the long run, the high up-front cost dooms most farmers to missing out on these opportunities. Now, there is no subsidy or funds from other independent sources for the small-scale farmers in the developing countries, such as Nigeria, to afford to purchase and maintain those precision technologies. A further issue is the difficulty of the technical know-how in terms of running and managing Precision Agriculture instruments. Smallholders in developing countries are often not trained enough to understand the data from GPS and IoT sensors and other modern tools (Tey and Brindal, 2012). Inadequate access to educational programs and agricultural extension services also enhances this problem because it becomes hard for farmers to optimally utilise precision agricultural technologies. It also helps to avoid adopting new technologies, as farmers are reluctant to spend money on instruments with which they are unfamiliar. Thus, lack of facility and the cost of acquiring and implementing precision agricultural technologies remain major impediments to their adoption in developing nations. Some of the precision agriculture technologies, especially those based on IoT technologies, depend on internet connectivity to operate efficiently. But in the remote and rural areas of the developing world, internet connections can be scarce or totally non-existent (Kumar *et al.*, 2024). This lack of fundamental investment complicates the application of technologies whose effectiveness depends on wired data links or real-time tracking, for example, IoT sensors to monitor irrigation needs or drone coverage for crop concerns. Besides, the existing transport and energy infrastructure in the rural areas poses additional challenges to the usage of precision agricultural technologies (Gbadamosi and Olorunfemi, 2016). Equipment like UAVs and tractors that form part of precision agriculture applications need to be powered constantly, an aspect that is always elusive in many developing countries. Lack of infrastructure and the relevant necessary equipment means poor application of the technologies that precision agriculture offers to farmers, mostly in rural areas. These challenges, in addition to a lack of equal access to technology and the possibility of uses of digital technology to augment and expand inequalities identified between large commercial farms and smallholder farmers, paint the future of African agriculture with potential inequalities. While large-scale, well-endowed farms are able to embrace and incorporate precision agricultural technologies, smallholder farmers, who could also benefit enormously from improved productivity, do not get service. Adoption of IoT technology in agriculture is not without its obstacles. One factor preventing IoT device adoption has been noted as being a lack of technical expertise. To properly integrate IoT technology into their agricultural methods, farmers might need assistance and training (Jabbari *et al.*, 2023). Meeting these challenges calls for collective action from governments, non-governmental organisations, and intergovernmental organizations. Subsidies—in the form of cash injection, cheap credit, or grants—could assist smallholder farmers to cover a major proportion of Precision agricultural technologies upfront costs. Also, expenditures on education and training would help farmers acquire the technical know-how to manage precise instruments productively. Lastly, sustainable advancement in rural physical capital, particularly internet and reliable energy, is important in improving the use of precision agriculture technologies in the developing countries.

4.0 Conclusion

The findings presented in this work highlight the prospects of the modern cropping systems based on the principles of precision agriculture. On this basis, Precision agriculture technologies demonstrate a progressive action plan that would lead to improved crop yields, better uses of resources and generally the sustainability of the environment in agricultural production. Nevertheless, issues concerning the cost of implementing these technologies such as, infrastructure, or technical know-how affects the farming fraternity and should be dealt with, in order to make the realized benefits a reality at all levels of farming across the globe.

4.1 Recommendations

i. Government and Policy Support: Tax credit rebates or affordable interest rates on funds required for precision agriculture technology should be offered by governments. The Precision agricultural technologies should also feature in government food production, sustainable agriculture, and climate change policies.

ii. Training and Capacity Building: To operate and maintain precision devices, farmers require special education and training. Various farmers, with the help of agricultural extension services, universities, and international agricultural organisations can provide such programs.

iii. Infrastructure Development: Precision agricultural technologies that introduce the use of IoT require a stabilised framework; this consists of the internet. Therefore, expenditure in these technologies can yet aid the extension of rural digital facilities.

iv. Financing and Subsidy Models: Policies should also be proposed to supply capital for small farmers to purchase Precision agricultural technologies by cooperatives or through public, non-private partnerships. Asking to "premium" risks, small farmers could coordinate an order of precise technology and divide the gains in efficiency and productivity.

v. Research and Development: More studies should develop literature on how to improve Precision agricultural technologies acceptance, how to reduce the cost of the materials, and adapt them to the different production systems prevalent in the developing world. Second, empirical examination of the resilience of Precision agricultural technologies on power dynamics in the rural labour market and economy has to be done.

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