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EXPLORING A MOBILE APPLICATION FOR PEST AND DISEASE SYMPTOMATIC DIAGNOSIS IN FOOD CROPS IN NIGERIA: IMPLICATIONS OF ITS USE BY SMALLHOLDER FARMERS IN SUB-SAHARAN AFRICA

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ABSTRACT

Crop pests and diseases are major impediments to food security in sub-Saharan Africa. Timely and accurate diagnosis of invasive crop pests and diseases promote crop protection efforts. The use of digital mobile application technology and image processing tools for precision agriculture and pest identification and monitoring is gaining attention but limited research has tested its accuracy, especially in sub-Saharan Africa. In this study, the accuracy of Plantix - your crop doctor (a general-purpose mobile application for plant pests and diseases diagnosis) was evaluated on common pests and diseases of some staple crops grown in South-Western Nigeria. The results showed 90-100% accuracy of major pest and disease symptoms detected on maize (*Zea mays*), okra (*Abelmoschus esculenthus*), cassava (*Manihot esculenta*), and plantain (*Musa paradisiaca*), and the application showed 100% accuracy when used to diagnose similar crop types, but that are healthy. However, pest symptoms on Celosia (*Celosia argentea*), Amaranth (*Amaranthus* sp.), and Roselle (*Hibiscus sabdarifa*) were not detected by the mobile application, probably because these crops were not yet included in the database of this application. The exploration of this mobile application can provide technical services for farmers. There is a need to update the database of Plantix with local and indigenous crops in sub-Saharan Africa and develop home-grown mobile applications for disease and pest diagnosis and monitoring.

Keywords: Diagnosis, "Plantix-your crop doctor", Accuracy, Disease, Pest.

INTRODUCTION

Plant pests and diseases are naturally occurring phenomenon that has significant consequences on crop yield and ultimately food production. The estimate by Food and Agricultural Organisation FAO (2021) revealed that 40% of global crops are lost to pests annually, with up to $220 billion in losses associated with plant diseases and $70 billion linked to damage by invasive insect pests. These pests threaten farmers' livelihoods and are a major setback to achieving the sustainable development goal of zero hunger and food security.

Food insecurity is critical in sub-Saharan Africa (SSA), and recent threats by invasive pests have caused massive damage to crops leading to significant yield losses. Some of the important examples are the South American tomato pinworm, *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) (Borisade *et al*., 2017) and the Fall armyworm (*Spodoptera frugiperda*) (Goergen *et al*., 2016) which invaded Nigeria in 2016 and has spread to other African countries. Their invasion appears to be climate-change-induced and it is expected that there will be more reports of this phenomenon. Based on the IPPC (2021) report, there are strong indications that climate change has expanded the host of pests and their geographic distributions, and this has increased the risk of pest introduction to new areas. Farmers and extension agents presumably face the problem of diagnosis and control of invasive species apparently because these pests are new in that location. This may lead to infections not detected or reported early or the use of the wrong management strategy (Wani *et al*., 2022). Using traditional methods for pest diagnosis is usually tedious because it is time and energy-consuming, and requires contact with an expert (Wani *et al*., 2022). This is even more problematic for smallholder farmers in rural communities where there is limited knowledge of pest and disease diagnosis, effective crop protection methods, and limited access to extension services. For instance, during the COVID-19 lockdown, farmers lacked access to extension information, visits, and production inputs (Nchanji and Lutomia, 2021; Nchanji *et al*., 2021). Hence, farmers could not be trained because extension workers could not render traditional face-to-face consultancies due to restrictions of movement.

The limitations caused by pest diagnostic problems, access to experts and extension agents, or potential movement restriction imposed a need for alternative diagnostic platforms, especially among small-holder farmers in vulnerable communities. The traditional method involves direct physical consultations between specialists and farmers, who examines the plant symptoms, conduct relevant analysis, and make recommendations (Siddiqua *et al.*, 2022). Advances in digital technology can help in overcoming farmers' information limitations and provide access to knowledge on extension information and novelty in agricultural productivity (Deichmann *et al.*, 2016). Furthermore, Information and Communication Technology can also improve technical services and connect smallholder farmers with useful and relevant resources (Beverley and Thakur, 2021). Undoubtedly, mobile phones and the Internet is vital to agricultural development (Evans, 2018) and it is becoming increasingly accessible to rural dwellers. Several crop-related mobile applications are now available, including those involved with disease identification and detection, and providing recommendations to users (Siddiqua *et al.*, 2022). Farmers can therefore be encouraged to use mobile applications to access technical services for themselves, and also interact with other farmers around the world since this technology promises to be a cheaper extension tool among smallholder farmers in sub-Saharan Africa (Omulo and Kumeh, 2020). Recent studies have reported the use of mobile applications for the development of disease diagnosis in tomatoes (Loyani, and Machuve, 2021; Chen *et al.*, 2022), maize (Moawad and Elsayed, 2020; Niyomwungere *et al.*, 2022), and coffee (Divyashri *et al.*, 2021). However, few applications have been widely tested globally for general-purpose real-world use.

Siddiqua *et al.* (2022) recently reported "Plantix-your crop doctor" as one of the best applications with the ability to identify and detect plant diseases. The application uses image detection technology, has an extensive database of plants, provides recommended treatments, and has an interactive community-based system where farmers can interact and learn from one another. This application is a free digital tool that uses mobile phones to diagnose plant diseases in seconds. This tool could be revolutionary for farmers in rural communities, but its adoption is very low as it is still largely unknown in SSA. Furthermore, the accuracy of this mobile application in detecting diseases in local crops is unclear as there is no publicly accessible information that has analysed its level of accuracy in detecting symptoms of commonly grown crops in Nigeria. Therefore, this study assessed the accuracy of the mobile app, Plantix - your crop doctor, for pest and disease symptom identification and diagnosis of some staple crops consumed in Nigeria.

MATERIALS AND METHODS

Research Site

The data were collected on farms in Ejigbo, Nigeria. The pictures of plant parts were taken between July and September 2022 and all diagnoses were completed by January 2023.

Source of Mobile Application

The mobile application, "Plantix-your crop doctor", was downloaded from the Google Play store and installed on Android smartphones (Infinix Smart 5 and Gionee phone).

Crop tested

The experiment was conducted on staples and commonly consumed vegetable crops in Southwest Nigeria, including maize (*Zea mays*), okra (*Abelmoschus esculenthus*), plantain (*Musa paradisiaca*), cassava (*Manihot esculenta*), celosia (*Celosia argentea*), Roselle (*Hibiscus sabdarifa*) and amaranth (*Amaranthus* spp).

Picture of plant and disease symptoms

Apart from celosia, ten pictures of specific symptoms on disease- or pest-infected plant parts were captured on all tested crops. Ten pictures were also taken on different healthy plant parts. Pictures of symptoms taken of plant parts damaged include 1. Perforated leaves with frasses of fall armyworm on maize plant. 2. Perforation on leaves caused by flea beetle on okra and roselle plants. Yellow mottling patterns caused by cassava mosaic virus on Cassava plant. 3. Brown leaf spots and large necrotic disease on plantain leaves caused by yellow and black sigatoka on plantain plant, 4. Insect perforated leaves on amaranths 5. Leaf webbing with frass remains or eaten leaves by caterpillars on Celosia. For all the crops tested, pictures of healthy equivalents were also captured apart from Okra and Roselle where all plants were infested.

Processing of image of plant disease captured

Pictures were captured with the phone camera and stored to be processed later or processed immediately using the mobile application.

Data collection

Data were collected based on the response output from the application. These were also compared with data from healthy plants.

The Percentage Accuracy (PA) of the app was calculated for each tested crop by this formula:

$$PA = \frac{\text{number of accurate results}}{\text{Total number of pictures taken}} \times 100$$

RESULTS

Processing and Disease symptoms Diagnosis by "Plantix-your crop doctor"

The pictures of the diseased parts of the crops are shown in Table 1.

Table 1: Diseased plant and causative organisms.

S/N	Crops	Plant Part Images	Symptoms	Causative Organism
1	Plantain		Brown leaf spot, large necrotic disease.	Black sigatoka
2	Cassava		Yellow spots on leaves, stunted growth, leaf deformation with curling shape.	African Cassava mosaic virus
3.	Okra		Feeding damage with small shot-like holes.	Flea beetles

4	Maize		Feeding damage on all plant parts and perforated leaves, frass on leaves	Fall armyworm
5.	Amaranth		Perforated leaves	Grasshopper
6.	Celosia		Leaf perforation and webbing, perforated leaves	Webworm
7.	Roselle		Feeding damage with small shot - like holes.	Flea beetles

The application processed the pictures in less than 10 s when there was a reliable internet connection. It gave diagnostic information (Figures 2 and 3) as well as corresponding proposed treatment measures. It was observed that the diagnostic information captured by the application is processed accurately when the pictures were taken within 2 cm of the targeted plant part. Blurry pictures may be rejected.

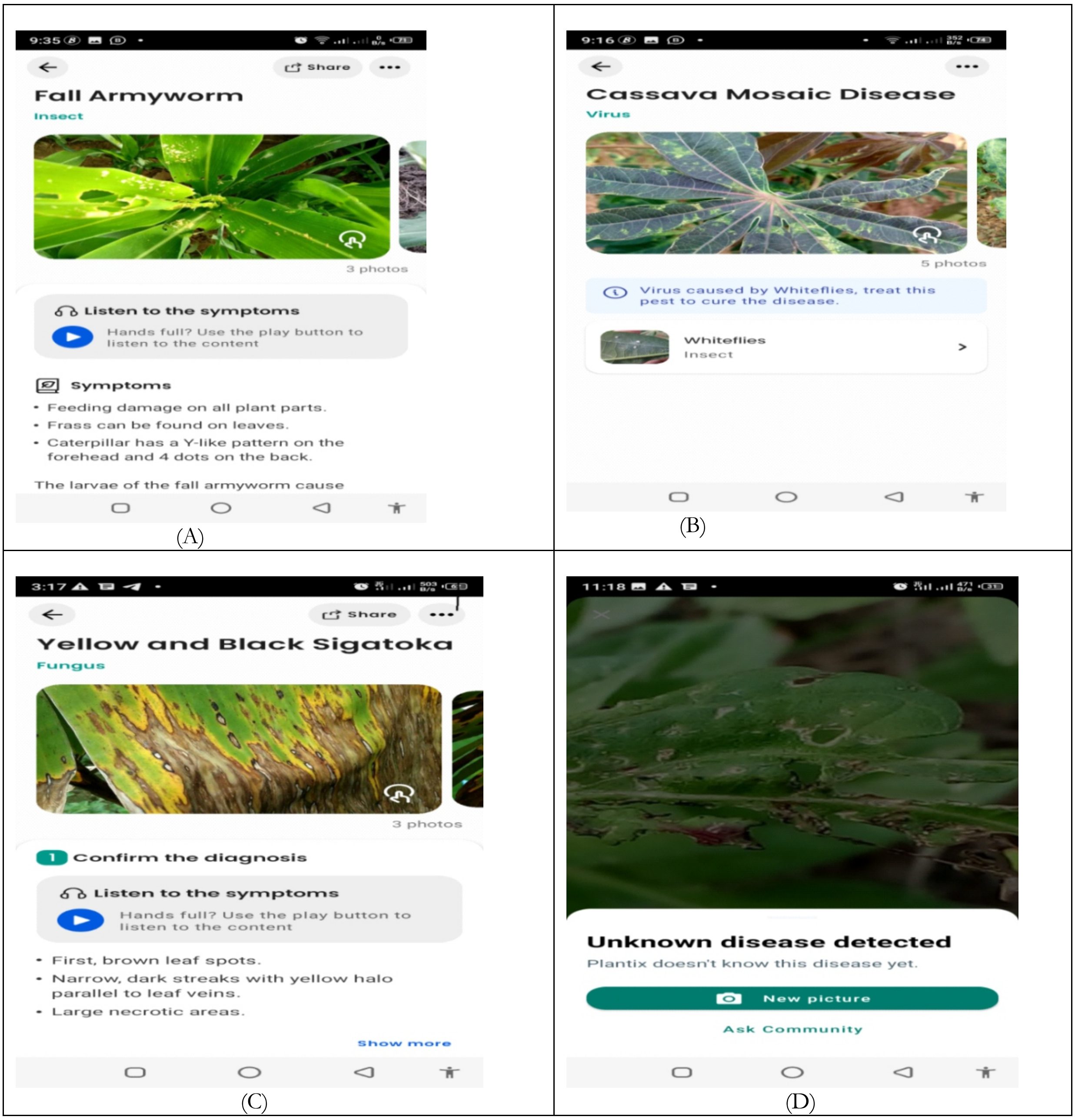
Percentage Accuracy of "Plantix-your crop doctor" in Crop disease symptom diagnosis

The mobile application showed 90-100% accuracy in the symptomatic diagnosis of pests and diseases caused by fall armyworm on maize, flea beetle on okra, black sigatoka on plantain, and cassava mosaic virus on cassava. Specifically, 100% of fall armyworm symptoms were accurately detected in maize. Also, 100% accuracy was obtained for cassava mosaic virus symptoms on cassava and sigatoka on plantain and cassava mosaic virus on cassava. The application was 90% accurate in detecting flea beetle symptoms in okra. However, the application could not detect the disease symptoms captured for amaranth, roselle, and celosia (Table 2). The output of Plantix for each disease symptom is shown in Figure 1.

When the application was used to test healthy plant parts of maize, cassava, and plantain, they were correctly recognised as healthy with 100% accuracy. However, Plantix could not detect healthy pictures of amaranth and celosia plant leaves (Table 2). The application output for each healthy plant part is shown in Figure 2.

Table 2: Percentage accuracy of mobile application ("Plantix-your crop doctor") diagnosis of diseased crop symptoms and detection of healthy crop status.

S/N	Plants tested	Plant part photographed (replicates)	Diseased plants			Healthy plants		
			Condition (Symptoms)	Number of accurate diseased symptoms diagnosis	% accuracy of disease diagnosed	Condition	Number of accurate healthy status detected	% accuracy of healthy status detected
1	Maize	10	Fall armyworm damage	10	100%	Healthy	10	100%
2	Cassava	10	Cassava mosaic disease	10	100%	Healthy	10	100%
3	Plantain	10	Yellow and black sigatoka	10	100%	Healthy	10	100%
4	Celosia	7	Leaf webbing with frass by webworm	0	0%	Healthy	10	undetected
5	Amaranth	10	Leaf perforation by insect	0	0%	Healthy	10	undetected
6	Roselle	10	Flea beetles damage and perforation	0	0%	Unavailable	-	-
7	Okra	10	Flea beetles damage and perforation	9	90%	Unavailable	-	-


Share
Fall Armyworm
Insect
3 photos
Listen to the symptoms
Hands full? Use the play button to listen to the content
Symptoms
Feeding damage on all plant parts.
Frass can be found on leaves.
Caterpillar has a Y-like pattern on the forehead and 4 dots on the back.
The larvae of the fall armyworm cause
(A)
Cassava Mosaic Disease
Virus
5 photos
Virus caused by Whiteflies, treat this pest to cure the disease.
Whiteflies
Insect
(B)
Share
Yellow and Black Sigatoka
Fungus
3 photos
1 Confirm the diagnosis
Listen to the symptoms
Hands full? Use the play button to listen to the content
First, brown leaf spots.
Narrow, dark streaks with yellow halo parallel to leaf veins.
Large necrotic areas.
Show more
(C)
Unknown disease detected
Plantix doesn't know this disease yet.
New picture
Ask Community
(D)

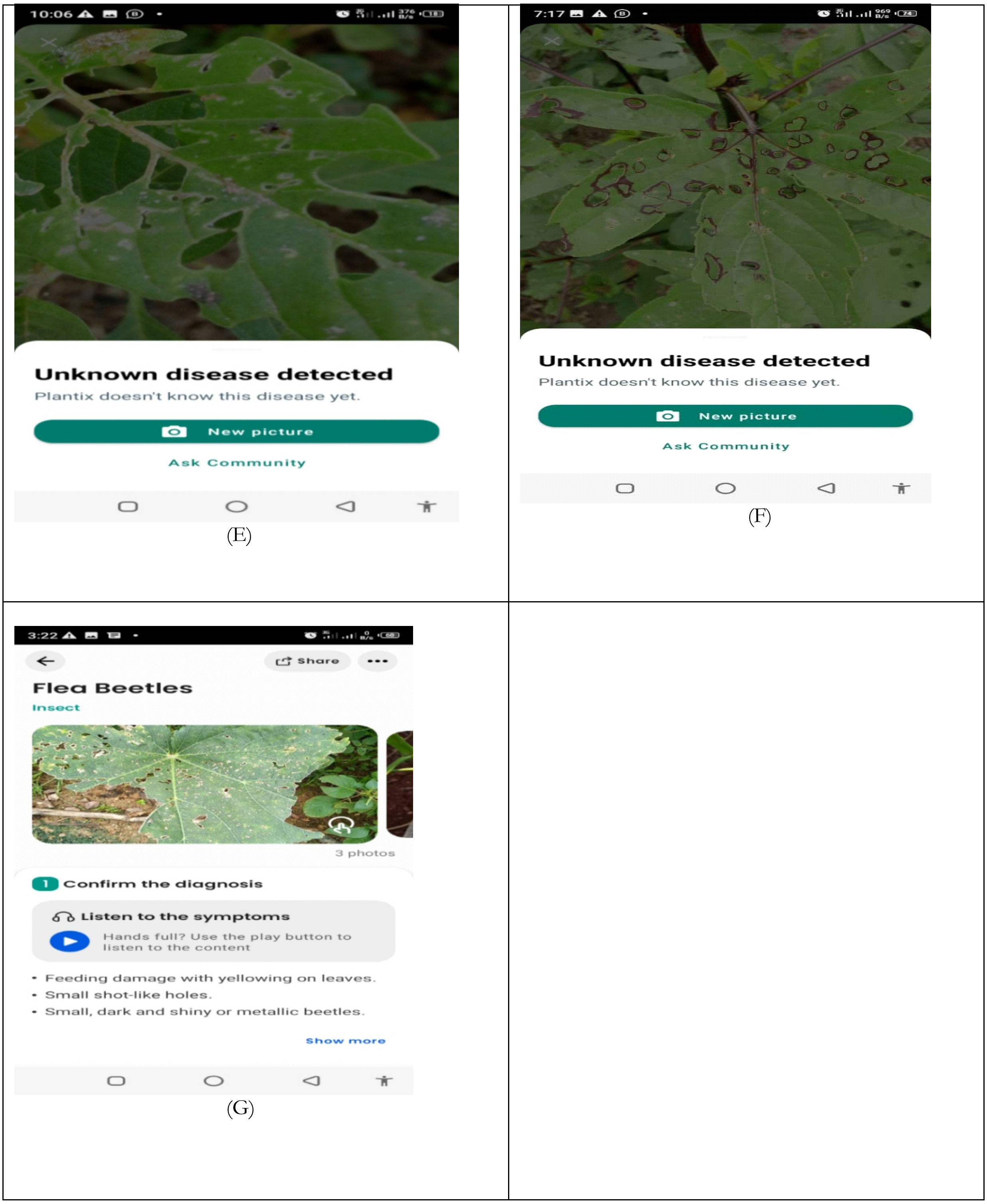


Figure 1: Screenshot examples of "Plantix-your crop doctor" application diagnosis result for diseased plants of (A) Detected fall armyworm on maize; (B) Detected cassava mosaic virus symptoms; (C) Detected Sigatoka disease symptom on plantain; (D) Undetected damage on Celosia; (E) Undetected damage on *Amaranthus*; (F) Undetected damage on Roselle (G) Detected Flea beetle damage on Okra.

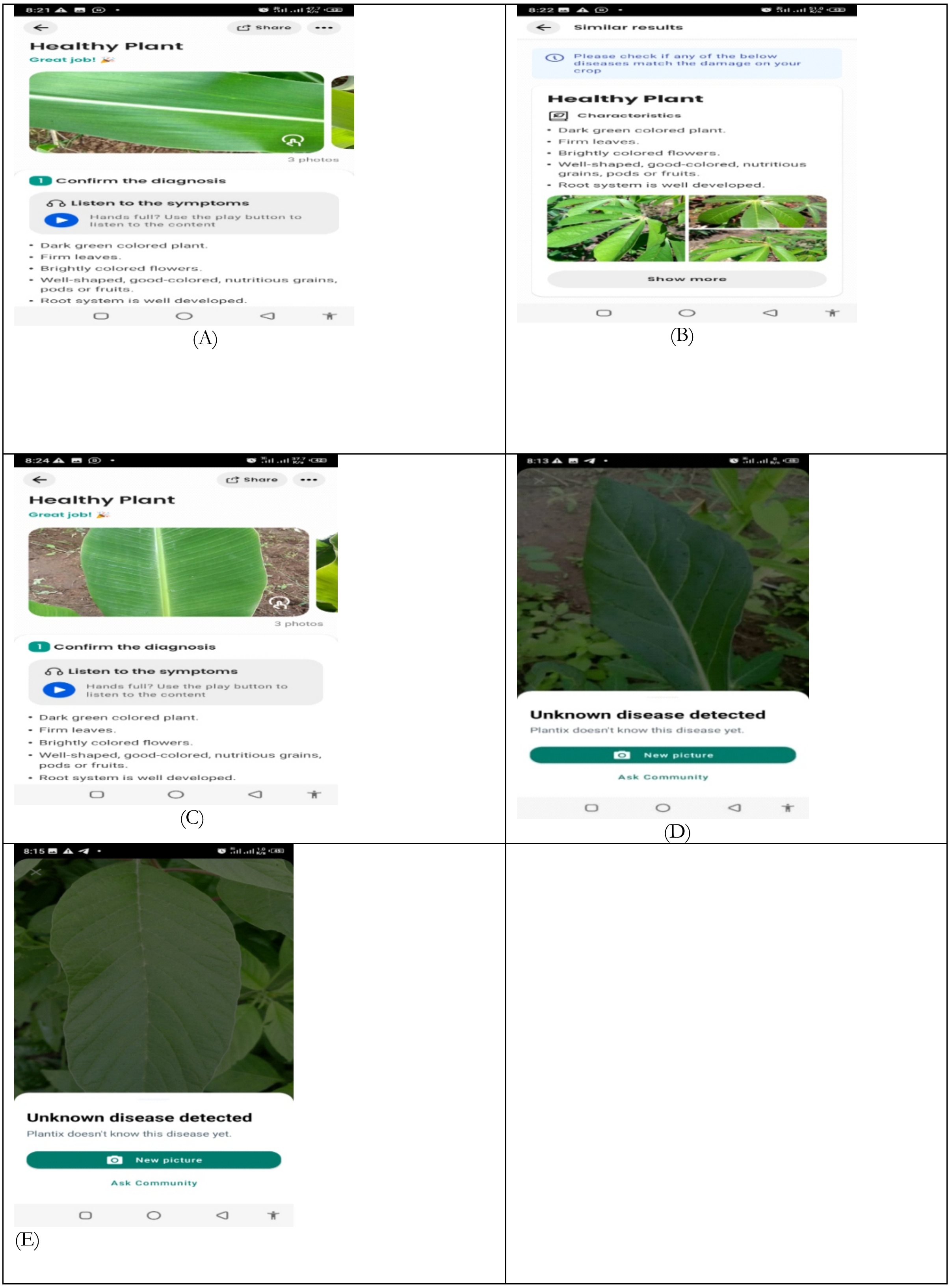


Figure 2: Screenshot examples of plantix application diagnosis result for healthy plants (A) healthy maize; (B) healthy cassava; (C) healthy plantain; (D) healthy Celosia; (E) healthy Roselle.

DISCUSSION

This study tested the accuracy of a mobile application, Plantix-your plant doctor, in the symptomatic diagnosis of common pests and diseases of some staples in Nigeria. It accurately detected some widely known pests and diseases including fall armyworm, flea beetle, yellow and black sigatoka, and cassava mosaic virus on maize, okra, plantain, and cassava, respectively. However, disease symptoms of some locally consumed vegetables including insect perforated leaves on Roselle and Amaranth usually caused by grasshoppers, and webbing of celosia leaf by insect caterpillars was not detected.

The lack of detection of these locally consumed vegetables is probably because these crops have not been included in the database. This is further confirmed since this application could not detect the healthy leaves of these local vegetables. Hence, there is a need for the continuous addition of indigenous crops into the Plantix database, as it would widen its usage in SSA. Plantix-your plant doctor works by identifying pests and diseases using artificial intelligence and machine learning and it directly uploads images taken by users into its servers using the internet (CGRAI, 2021). Users can also interact with experts and other stakeholders by submitting images of different indigenous crops, which could be incorporated into the database. This implies that the more this application is used in this region, the higher the potential to improve its accuracy. Thus, the inability of Plantix to diagnose diseases in some of the undetected crops could be overcome by submitting and saving these plants into the Plantix database, thereby making these pictures accessible to experts around the world and facilitating accurate diagnosis of these pests and diseases.

Our result showed that apart from crops not detected, only flea beetle symptoms on Okra was detected with 90% accuracy. An AIPES application for identifying fall armyworm has shown 100% accuracy during training and 87% accuracy for validation (Prabha *et al.*, 2021) and VGG_{16}, VGG_{19}, InceptioV3, and MobilenetV2 models have shown 99-100% accuracy for fall armyworm identification (Ishengoma *et al.*, 2021). InceptioV3 model tool have also shown 99% confidence accuracy in detection of sigatoka in banana (Sanga *et al.*, 2020). Plant village Nuhu, a mobile application has shown 65% symptomatic diagnosis of cassava diseases (Mrisho *et al.*, 2020). The possible reasons for the wrong diagnosis of the remaining 1 of 10 replicates (of flea beetle on Okra) tested were likely because the samples captured had symptoms of more than one disease. For plant parts with multiple symptoms, one major limitation of the application is that it does not appear to identify more than one disease at a time. For example, while the okra plant sampled had an obvious perforation caused by flea beetle, it also had symptoms caused by other pests or pathogens. Therefore, the application identified the symptoms of the pathogen rather than those of the flea beetle. The inability to detect multiple simultaneous diseases and the assumption that only one disease is present in each image has previously been identified as a major limitation in most of the major application models (Wani *et al.*, 2022). Another limitation identified in this study is that the application gives a general name to insect pests whose presence or symptoms may look alike and belong to the same genus rather than the same species. For example, the application correctly recognised the pest on okra as flea beetle, but there are different species of flea beetle. Understandably, the inability of the application to differentiate between two similar species in the same genus may be associated with the fact that most of the pests in this category are largely similar morphologically when observed and generally have similar symptoms. Therefore, it will be recommended that though the use of standardized mobile applications solves the immediate problem of identifying symptoms caused by pest infestation, there is a need to further confirm the exact status of some of the pests using microscopic and molecular methods.

The immediate detection of major pests and diseases such as flea beetle, black sigatoka, and cassava mosaic virus including the invasive fall armyworm, with 90-100% accuracy emphasizes its importance in SSA for detecting and monitoring major pests and invasive species. However, the inability of this application to detect pests on locally consumed vegetables, as observed in this study, does not limit its use for pest and disease monitoring in crops, since the application can be improved. Also, the application could be useful in tracking new and invasive pests, monitoring and forecasting, ensuring early warning, and providing an environmentally-safe Integrated Pest Management strategies. The fact that the application provides pest management recommendations shows that farmers can remotely access technical services. Also, extension agents can use it to access needed up-to-date information on pest management through their interaction with other farmers in Africa and globally on up-to-date and environmentally friendly IPM methods, thus aiding the dissemination to local smallholder farmers.

The use of smartphones is growing tremendously in Africa. It is estimated that its use will increase from 49% in 2021 to 61% and 613 million subscribers by 2025, and a third of new subscribers will come from Nigeria and Ethiopia (GSMA report, 2022). Exploring mobile tools for solving agricultural problems and disseminating agricultural information is therefore critical to the future of IPM in Africa. Our result confirmed that the mobile application used effectively detected some pests and diseases associated with some staples in Nigeria though some locally consumed vegetables could not be detected. The level of accuracy is expected to increase as the number of African users increase. Therefore, there is a need to increase awareness of the availability of Agricultural and Crop Protection mobile applications that can be used to support agricultural production systems through early pest and disease diagnosis. These applications will also educate, support and motivate farmers on IPM strategies that are environmentally friendly thereby avoiding pollution associated with the excessive use of pesticides.

The revolution stimulated by the increased use of mobile applications for Crop Protection can only take place if small-scale farmers, which form the majority of farming communities in SSA, are practically involved. Categories of smartphone owners span through the ages of 14 to 60 years which is the age bracket of practicing farmers across sub-Saharan regions of Africa (Simone, 2021). Therefore, effective digital technology must preferably be on android powered phones that are widely used by small-scale farmers.

"Plantix-your crop doctor" is one of the best applications with the ability to identify and detect plant diseases (Siddiqua *et al.*, 2022). The application is usable in SSA because it is free and uses image detection technology available on most widely used mobile android phones in the region, with an extensive diversity of plants in its database. Also, it provides recommended treatments and an interactive community-based system that will help farmers in this region to interact with other stakeholders around the world. Though the application requires the internet to diagnose pests and diseases, farmers in remote areas without internet access can use it to store pictures of disease symptoms taken on their farms while diagnosis and IPM management recommendations could follow when there is an internet service. This application is also useful to extension agents or officers who are the immediate contact and solution providers to farmers. They can receive pictures of damage symptoms sent by farmers and access useful information diagnostic and IPM information needed by farmers. They can also interact with other stakeholders within the community-based platform provided by the mobile application providers. This information can be used to train farmers during the on-farm training programme. Despite the relevance of "Plantix-your crop doctor" in providing a complete solution for crop production and management, the limitations are majorly on its regionalization. Its inability to detect some locally grown crops may also limit its use. The application will be more usable locally if it is translated into other local languages in SSA. For now, the application is available in 18 languages and all the major Indian languages are covered (Simone, 2021), while many local languages in SSA regions have not been covered. There is a need for rapid popularisation of this application among all stakeholders, especially farmers in this region. Alternatively, other applications can be made targeted toward locally grown crops.

CONCLUSION

In conclusion, "Plantix-your crop doctor" application showed 90-100% accuracy in identifying disease symptoms caused by fall armyworm on maize, flea beetle on okra, black sigatoka on plantain, and cassava mosaic virus on cassava but could not identify symptoms in three locally consumed vegetables (amaranth, roselle, and celosia). There is a need to incorporate the unidentified locally consumed crops into the application database and promote the use of this mobile application in SSA, as it could facilitate prompt diagnosis and recommend an appropriate environmentally friendly strategy for controlling plant pests and diseases thereby ensuring food security.

REFERENCES

Beverley, C. and Thakur, M. 2021. Plantwise: A Knowledge and Intelligence Tool for Food Security through Crop Protection. In: Plant Diseases and Food Security in the 21st Century. Plant Pathology in the 21st Century, P. Scott, R. Strange, L. Korsten, M.L. Gullino (editors), 23 May 2021. Springer, Cham, pp. 231-248. doi:10.1007/978-3-030-57899-2_11

Borisade, O.A., Kolawole, A.O., Adebo, G.M. and Uwaidem, Y.I. 2017. The tomato leaf miner (*Tuta absoluta*) (Lepidoptera: Gelechiidae) attack in Nigeria: effect of climate change on over-sighted pest or agro-bioterrorism? *Journal of Agricultural Extension and Rural Development,* 9:163-171. doi:10.5897/JAERD2017.0856.

CGIAR, 2021. Plant Disease Diagnosis Using Artificial Intelligence: A Case Study of Plantix. Available online https://bigdata.cgiar.org/digital-intervention/plant-disease-diagnosis-using-artificial-intelligence-a-case-study-on-plantix/. Accessed on 05th December, 2022.

Chen, H.C., Widodo, A.M., Wisnujati, A., Rahaman, M., Lin, J.C.W., Chen L. and Weng C.E. 2022. AlexNet convolutional neural network for disease detection and classification of tomato leaf. *Electronics,* 11:951. doi:10.3390/electronics11060951

Deichmann, U., Goyal, A. and Mishra, D. 2016. Will digital technologies transform agriculture in developing countries? *Agricultural Economics,* 47(S1):21-33. http://hdl.handle.net/10986/24507

Divyashri. P, Pinto, L. A., Mary, L., Manasa. P. and Dass, S. 2021. The Real-Time mobile application for identification of diseases in coffee leaves using the CNN Model, 2021 Second International Conference on Electronics and Sustainable Communication Systems (ICESC), Coimbatore, India, 1694-1700 pp. doi:10.1109/ICESC51422.2021.9532662

Evans, O. 2018. Digital agriculture: Mobile phones, internet & agricultural development in Africa. https://mpra.ub.uni-muenchen.de/90359/1/MPRA_paper_90359.pdf MPRA Paper No. 90359, University Library of Munich, Germany, posted 05 Dec 2018 09:14 UTC. Accessed 12th of November 2022.

FAO (Food and Agricultural Organization). 2021. Climate change fans spread of pests and threatens plants and crops, new FAO study. Accessed 15th January 2023. https://www.fao.org/news/story/en/item/1402920/icode/

GCMA Report 2022. The mobile economy Sub-Saharan Africa. https://www.gsma.com/mobileeconomy/wp-content/uploads/2022/10/The-Mobile-Economy-Sub-Saharan-Africa-2022.pdf. Accessed 04th of February 2023.

Goergen, G., Kumar, P.L., Sankung, S.B., Togola, A. and Tamò, M. 2016. First report of outbreaks of the fall armyworm *Spodoptera frugiperda* (JE Smith) (Lepidoptera, Noctuidae), a new alien invasive pest in West and Central Africa. *PloS One,* 11:e0165632. doi:10.1371/journal.pone.0165632

Ishengoma, F. S., Rai, I. A., and Said, R. N. 2021. Identification of maize leaves infected by fall armyworms using UAV-based imagery and convolutional neural networks. *Computers and Electronics in Agriculture*, 184:106124. doi:10.1016/j.compag.2021.106124

IPPC Secretariat. 2021. Scientific review of the impact of climate change on plant pests – A global challenge to prevent and mitigate plant pest risks in agriculture, forestry and ecosystems. Rome. FAO on behalf of the IPPC Secretariat. Accessed 15th January 2023. doi:10.4060/cb4769en

Loyani, L. and Machuve, D. 2021. A deep learning-based mobile application for segmenting *Tuta absoluta*'s damage on tomato plants. *Engineering, Technology & Applied Science Research,* 11:7730-7737. doi:10.48084/etasr.4355

Moawad, N. and Elsayed, A. 2020. Smartphone application for diagnosing maize diseases in Egypt. In: 14th International Conference on Innovations in Information Technology (IIT) IEEE, pp. 24-28. doi:10.1109/IIT50501.2020.9299067

Mrisho, L. M., Mbilinyi, N. A., Ndalahwa, M., Ramcharan, A. M., Kehs, A. K., McCloskey, P. C., Murithi, H, Hughes, D.P.,and Legg, J. P. 2020. Accuracy of a smartphone-based object detection model, Plant Village Nuru, in identifying the foliar symptoms of the viral diseases of cassava–CMD and CBSD. *Frontiers in Plant Science*, 11:590889. doi:10.3389/fpls.2020.590889

Nchanji, E.B. and Lutomia, C.K. 2021. Regional impact of COVID-19 on the production and food security of common bean smallholder farmers in Sub-Saharan Africa: Implication for SDG's. *Global Food Security*, 29:100524. doi:10.1016/j.gfs.2021.100524

Nchanji, E.B., Lutomia, C.K., Chirwa, R., Templer, N., Rubyogo, J.C. and Onyango, P. 2021. Immediate impacts of COVID-19 pandemic on bean value chain in selected countries in sub-Saharan Africa. *Agricultural Systems*, 188:103034. doi:10.1016/j.agsy.2020.103034

Niyomwungere, D., Mwangi, W. and Rimiru, R. 2022. Multi-task neural networks convolutional learning model for maize disease identification. In: IST-Africa Conference, IEEE, IST, Africa, pp. 1-9. doi:10.23919/IST-Africa56635.2022.9845568

Omulo, G. and Kumeh, E.M. 2020. Farmer-to-farmer digital network as a strategy to strengthen agricultural performance in Kenya: A research note on 'Wefarm'platform. *Technological Forecasting and Social Change,* 158:120120. doi:10.1016/j.techfore.2020.120120

Prabha, R., Kennedy, J. S., Vanitha, G., Sathiah, N. and Priya, M. B. 2021. Artificial intelligence-powered expert system model for identifying fall armyworm infestation in maize (*Zea mays* L.). *Journal of Applied and Natural Science*, 13:1339-1349. doi:10.31018/jans.v13i4.3040

Sanga, S. L., Machuve, D. and Jomanga, K. 2020. Mobile-based deep learning models for banana disease detection. *Engineering, Technology & Applied Science Research*, 10:5674–5677. doi:10.48084/etasr.3452

Simone, S. 2021. Meet Plantix, the smartphone app aiming to solve global food security problems: Orbit Shift Podcast. Accessed on the 3rd of February, 2023.

Siddiqua, A., Kabir, M.A., Ferdous T., Ali I.B. and Weston L.A. 2022. Evaluating plant disease detection mobile applications: quality and limitations. *Agronomy,* 12:1869. doi:10.3390/agronomy12081869

Wani, J.A., Sharma, S., Muzamil, M., Ahmed, S., Sharma, S. and Singh, S. 2022. Machine learning and deep learning based computational techniques in automatic agricultural diseases detection: methodologies, applications, and challenges. *Archives of Computational Methods in Engineering*, 29:641-677. doi:10.1007/s11831-021-09588-5