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論 文 内 容 の 要 旨

Chapter 1 Introduction

A 60% increase in agriculture production including vegetables is required to meet the projected 9.8 billion world population by 2050. Among foods, vegetables have the potential to increase food demand, however, it is subjected to several challenges. Among others, climate conditions greatly hinder vegetable production, this research focused on the marginalized small-scale farmers, specifically low-resourced tomato small scale farmers, in this research we termed them as labor constrained and ICT constrained small-scale farmers in Japan and Sub-Saharan Africa (SSA) respectively.

The research approached the challenges using a data-driven emerging technological transfer to enhance tomato production with a focus to reduce losses due to biotic (herein tomato pests ***Tuta absoluta***) and abiotic (herein microclimate) factors, to increase yield and alleviate food security concerns using ICT and Artificial Intelligence techniques.

Four chapters, **Chapter 2:** Smart agriculture application in labor constrained small scale horticulture farming, **Chapter 3**: A study of emerging technology in ICT constrained farmers **Chapter 4**: Image Recognition of tomato pest using deep learning and **Chapter 5:** Image recognition using gradient boosting based on multispectral, are hereby summarized.

Chapter 2 Smart Agriculture Application in Labor Constrained Small Scale Horticultural Farming

We focused at the problem of abiotic factors (herein microclimate) of labor constrained small-scale farmers in Japan. The solution to this was, we introduced and demonstrated a simplified smart agriculture system in greenhouse. Analytics results based on real-time data showed how it could be used reliably in actions for microclimate environment crop management. The approach based on ICT technological of smart agriculture system to labor constrained small-scale horticultural farmers to improve tomato production management. The real-time information composed of commercial inexpensive wireless sensor network devices and developed database for crop environment monitoring and management. Contrarily, an ICT based technological transfer to ICT constrained small scale farmers in SSA to tackle the problem of microclimate was not considered, we therefore, focused on a major problem to reduce losses due to biotic (herein tomato pest *T. absoluta*) factors, that has become a major threat to small-scale farmers production, which was later introduced in Chapters 3, Chapter 4 and Chapter 5.

Chapter 3 A study of Emerging Technology in ICT Constrained Farming

In this chapter, we studied factors that can be used to enhance impactful use of computer vison based early detection approach to tackle tomato pest *T. absoluta*. A comprehensive study of the demography and farmer information flow were done in the areas that are most affected by *T. absolut*a based on a questionnaire survey of small scale farmers of most *T. absolut*a prone areas in Tanzania. We studied and examined tomato farmers' knowledge on tomato pest *T. absolut*a damage and to devise recommended platform for introduction of deep learning based techniques to tackle *T. absolut*a.

In addition, results of experimental works, showed that a high correlation of decreased marketable tomato market was due to *T. absoluta* damages. Therefore, to solve this problem, a need for early image recognition techniques was suitable and recommended as an alternative approach to tackle the challenge. We further, used artificial intelligence techniques as discussed in chapters 4 and 5.

Chapter 4 Early Detection of Tomato Pest Using Deep Learning Technique

Tomato pest *T. absoluta* invasion can cause loss of up to 100%. It is therefore important for early pest identification for effective management option at early stages of tomato production to avoid economic losses. The main goal was to develop deep learning techniques based on computer vision as tomato pest early identification and quantification tools to strengthen phytosanitary capacity and systems for effective management option of *T. absoluta.*

The research's specific objectives are: (1) to develop a *T. absoluta* early identification Convolutional Neural Network (CNN) model under commonly practiced agriculture practices. (2) to develop early detection and quantification CNN models for Tomato infested by *T. absoluta* damage characteristics and quantification to enhance early detection.

In-house experiments (screen house) were carried in a SSA country Tanzania between August 2018 and May 2020. The planted tomato seedlings were inoculated with *T. absoluta* (4-8 larvae) to random plants on the second day after transplanting. High- and low-resolution images and multispectral images of tomato plants leaves were captured. Also soil moisture, air temperature, humidity, sunlight illuminance data were collected using a data logger. We used deep CNN architectures to develop models to identify *T. absoluta* invasion. The models were categoried as (i) image recognition models to classify tomato plants damaged by *T. absoluta* and (ii) ***T. absoluta* damage quantification model** – A deep CNN for determining the effects of *T. absoluta* in tomato plants. Four pre-trained CNN architectures, VGG16, VGG19 and ResNet and additional Inception-V3 model for quantification task, were used for training. For *T. absoluta* image recognition task, we evaluated performance on each classifier by considering accuracy of classifying the tomato canopy into correct category. Results showed VGG16 models out performing other models for all the three carried out dataset distribution ratios. Among the pretrained architectures, results showed that Inception-V3 yielded the best accuracy of 87.2 % and VGG16 had the lowest loss of 0.152 in estimating the severity status of *T. absoluta*. It should be noted that the pretrained models could also easily identify High Tuta severity status compared to other severity status (Low tuta and no tuta).

Chapter 5 Image Recognition Using Gradient Boosting Based on Multispectral Imaging

The objectives was using multispectal image analysis to investigate spectral characteristics of *T. absoluta* infested tomato plants under commonly practices agriculture practices and to investigate the use of multispectral indices in detecting *T. absoluta* damage tomato characteristics.

Multispectral images of tomato canopy were captured using Sequoia camera. Images were preprocessed using Pix4D software, the result as mosaicked calibrated reflectance map of respective spectral bands (red, green, red Edge and NIR) were further preprocessed in ArcGIS and ENVI software tools and finally background pixels were removed from individual plant canopy. The reflectance map was further used to calculate several multispectral image indices. Multispectral indices of individual tomato plant canopy were subjected to several statistical analysis, typical machine learning based on gradient boosting (Xgboost, LightGBoost and CatBoost) techniques were used for classification task.

Several spectral characteristics of *T. absoluta* affected plants and healthy plants were analyzed. Using gradient boosting on decision trees algorithms, bayesian optimization were adopted to find the best performing algorithm for *T. absoluta* classification using multispectral images.

Results showed catBoost model outperformed other models with accuracy of 79.4% and validation of 77.7% based on selected multispectral indices NDVI, GNDI, NRI and MARI. We further used

TreeExplainer algorithms to understand the model performance and also identify the multispectral indices with the highest contribution to the model. Results showed that multispectral indices NDVI (index of near-infrared and red) and GNDI (index of near-infrared and green) had high SHAP values. It implies that the information in the near-infrared reflectance contains high potential to detect plant disease not only from RGB imagery.

Conclusions and Future works

This research looked at the integration of ICT and artificial intelligence techniques to enhance tomato production based on a data driven emerging technological approach. We introduced and deployed smart agriculture system with real-time capability and for reliable monitoring within the greenhouse which showed how important it was to maintain well-balanced optimum growing microclimate environment for plant growth, the case of labor constrained small scale horticultural farming. Also, the spatiotemporal analysis results showed how reduction in energy required for greenhouse heating and cooling could be achieved.

For the case of small scale farmers in Japan, quality plays a very important role in tomato market and eventually earns more income. Small-scale farmers struggle to produce tomato fruits of high quality. A very first step would be based on the proper management and control of micro-climate environment conditions in green houses. Therefore, with proper micro-climate management, the crop growth would be attained at their favorable conditions. Eventually good quality tomato fruits would be achieved.

Owing to the application of ICT in labor constrained horticultural farming, we researched on alternative data driven emerging technological approaches to tackle tomato pest in ICT constrained horticultural farmers. Results based on field survey and in-house experiments data for artificial intelligence techniques, the developed CNN image recognition models could be used in early detection of *T. absoluta* at early stages of tomato growth.

The outcomes of this research showed that in order to increase crop growth yield, a need to adopt such data driven techniques to enhance tomato production that will eventually lead to increased crop yield for small scale horticultural farming. With an increase in horticulture crop yield, this would eventually contribute to the required increase of agriculture by 2.4% per year to meet the required food demand.

The applied smart agriculture system techniques could be transferred to other tomato greenhouses and eventually used by other horticultural farming.

The developed deep CNN models for *T. absoluta* affected tomato classification and quantification and gradient boosting models for classification, could be applied in establishment of damage status maps on a wide scale.

For further research, we recommend establishment of platform to gather small scale tomato farmer field *T. absoluta* status based on our developed artificial intelligence techniques. Agriculture experts and decision makers could eventually use to strengthen phytosanitary capacity and systems for effective management option of *T. absoluta.*

審 査 報 告 概 要

本研究では経営規模の小さいトマト農家に着目し，生物的（トマト害虫・トマトキバガ：*Tuta absoluta*）および非生物的（微気象）要因による損失を減らすことで収量を上げ，食料安全保障の懸念を軽減することを目的に，データ駆動型の情報通信技術（ICT）と人工知能（AI）の最新技術移転による生産環境改善につなげる課題に取り組んだ。日本の小規模トマト農家の労働力の軽減，生産力改善の対策として，温室内のワイヤレスセンサーネットワークの開発と実装を行い，積算 GDD（10℃を基温とした温量指数）とトマト収量との関係性を示し，温室内微気象環境による収量向上の可能性を示唆した。一方，サブサハラ・アフリカにおけるトマト害虫 *T. absoluta* の圃場への侵入は，最大 100％の損失被害を引き起こす可能性があり，生産初期段階での効果的な管理オプションが必要である。タンザニアにおける施設内（ネットハウス）で定期的に撮影取得したトマト葉の RGB 画像およびマルチスペクトル画像を用い，害虫被害個体の深層学習技術による早期特定モデル開発を行った。深層学習の結果，RGB 画像においては，VGG16 モデル分類器を用い 90%以上の精度での罹病葉特定，植生指数 NDVI，GNDI，NRI，および MARI 画像などの近赤外線領域を含む情報のキャットブーストモデルで 79.4％の精度での罹病葉検出が可能であることを示した。

農業分野・リモートセンシング分野におけるコンピュータービジョン技術の応用を示し，センサー技術を組み合わせたスマート農業による次世代生産技術を提案できた点において高く評価できることから，審査員一同は博士（農業工学）の学位を授与する価値があると判断した。