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REVIEW

Development of Sustainable Technologies to Increase Agricultural Productivity and Improve Food Security in Africa

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Abstract

Global food demand is expected to increase considerably, reflecting the predicted increase in global population. In sub-Saharan Africa (SSA), where it is reported that one in four people remain malnourished and the population is predicted to double by 2050, achieving food security in terms of quantity and quality is an immense challenge. Conversely, in SSA, agricultural production potential has not been fully realized owing to poor soil fertility and adverse environmental conditions. Moreover, these regions are vulnerable to climate change and infectious diseases. The second goal of the 17 sustainable development goals calls on all nations to achieve “Zero Hunger.” Through joint research, the Food Security in Africa project by the Japan International Research Center for Agricultural Sciences has promoted sustainable technology development to improve food security in SSA in three focus areas: enhanced rice production, utilization of regional crops, and effective resource utilization under integrated crop–livestock systems. In this review, we introduce the technical challenges and problems of agriculture in SSA, explain the project’s efforts to address them, and discuss future prospects. We believe that all diverse stakeholders involved need to continue to work together to contribute to the maintenance of food and nutrient supply in SSA.

Discipline: Crop Science
Additional key words: cowpea, crop–livestock integration, rice, yam

Introduction

Global food demand is expected to increase greatly in the future, reflecting the predicted expansion of the global population, which is estimated to increase by approximately 2 billion people in the next 30 years (United Nations 2019). However, there are currently 821 million people, more than one-ninth of the world population, who do not get enough food to eat (World Food Programme 2020). In sub-Saharan Africa (SSA), where one in four people is reported to remain malnourished, the population is expected to double by 2050, making the achievement of food security in terms of quantity and quality an immense challenge. Moreover, in developing regions such as SSA, agricultural production potential has not been fully realized owing to poor soil fertility and adverse environmental conditions. Many smallholder farmers in these areas do not consume massive quantities of water and chemical fertilizers, and thus are the least contributors to climate change; however, they are predicted to suffer the most from extreme weather events. SSA covers > 50% of the global potential land for cultivation, but only a small portion of this land meets the conditions suitable for agricultural production (Jayne et al. 2010, Hengl et al.

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2017). The limited agriculture production in this region is complicated by a number of factors, such as soil nutrient deficiencies, soil physical constraints, damage from pests and diseases, and suboptimal management systems (Giller et al. 2009, Hengl et al. 2017). Although the proportion of arable land in SSA has been steadily expanding since the 1950s, crop yields have remained low (Jayne et al. 2010). Furthermore, the region is vulnerable to climate change. Under such circumstances, in 2016, the second goal of the 17 sustainable development goals (SDGs) called on all nations to "end hunger, achieve food security and improved nutrition, and promote sustainable agriculture."

The Japan International Research Center for Agricultural Sciences (JIRCAS) has been pursuing the development of suitable technologies to increase agricultural productivity and improve food security by promoting international collaborative research with related organizations in Japan and overseas. Since 2016, JIRCAS has initiated one of its flagship projects—Food Security in Africa—targeting SSA in three focus areas: enhancement of rice production, regional crop utilization, and crop–livestock integration. These three focus areas were carefully selected according to the research specialties of JIRCAS and the local demands. In Africa, to meet the rapid increase in rice consumption in urban areas and rice imports, there is an urgent need to increase rice production in countries with large demand for rice to increase food production and save foreign currency. However, the amount of rice imported from overseas, such as Thailand, remains to be in large quantities. Compared with the important commodities in SSA (FAOSTAT 2020), such as maize and millets, rice has comparative advantages, such as ease of transportation, storage, and cooking, making it a suitable research target. We focus on the integrated improvement (in terms of productivity) required to deal with the rapid increase in rice consumption. Some of the poorest countries are distributed in the semiarid regions of West Africa (Niger, Burkina Faso, and Guinea; Gapminder 2020), where food and nutrition shortages are a major problem. Including those countries, to meet the food and nutrition demands of the people in West Africa, regionally important crops, such as millets, cassava, and common beans, have tremendous potential. As research targets among these regional crops, we focused on white Guinea yam (*Dioscorea rotundata*; hereafter yam) and cowpea (*Vigna unguiculata*), which have received less research attention compared with other crops such as sweet potatoes and common beans. We focused on the utilization of the diversity of genetic resources and breeding materials that were adapted to high productivity and local preference with their potential to alleviate widespread poverty and hunger in the region. In addition, dairy promotion is important as a research target because it has the advantage of a stable supply of animal protein sources, which is very important for the healthy development of humans. Thus, we also focused on the development of suitable technologies for sustainable crop production and livestock raising that can effectively deploy locally available resources. These identified research activities are designed based on the premise of improving sustainability with efficient utilization of resources, efficiently utilizing unused germplasm, and capturing the preferences of consumers and the needs of farmers. Our work was conducted with national and international partners in nominated countries facing the challenges of short life expectancy and low income (Gapminder 2020), and we have been making steady progress. In this review, we introduce the technical challenges and problems regarding agriculture in SSA, describe our efforts to address these challenges, and discuss future prospects.

"Enhancement of rice production" project

Rice has been the fastest growing food in terms of both production and consumption in SSA in the last few decades. However, the average rice yield of SSA is only approximately 2.2 t ha^{-1} (USDA 2020), which is much lower than the average of the world's major rice-producing regions (Global Yield Gap Atlas 2020). In addition, the gap between regional rice consumption and production in SSA continues to widen. The growing reliance on rice imports has created an economic burden and food insecurity in the residents of SSA. This anxiety became especially apparent during food riots in several major capitals between 2007 and 2008 (Berazneva & Lee 2013). Therefore, further increases in local production of rice continue to be an urgent priority to ensure food security in SSA. In 2008, the Japan International Cooperation Agency (JICA) announced the founding of the Coalition for African Rice Development (CARD) as an initiative to support self-help efforts to expand rice production in Africa. By 2018, the platform partnered with governments in 23 target countries and 11 international organizations, including JIRCAS, to reach its goal of doubling rice production from 2008 to 2018. JIRCAS conducted various research activities in close coordination with international initiatives such as the CARD and generated some tools for enhancing rice production, including field management and cultivation techniques in rainfed lowland conditions (JIRCAS 2019a). The CARD initiative achieved its goal to double the production of rice. Statistical figures suggest that the increase in the production of rice over the past decade was mainly due to an increase in the cultivation area, whereas improvements in productivity were limited (Maruo et al. 2018). Rice consumption increased further during the decade of the CARD initiative, and thus the increase in rice production did not lead to an improvement in self-sufficiency. Therefore, additional improvements in rice production are necessary. Low yield per unit area of rice and limited rice cultivation area remain the limiting factors in increasing rice production, and a continuous approach to increase both aspects is key to future improvement in self-sufficiency.

Under the "Rice production enhancement" project, we have developed essential components of efficient production of rice (e.g., breeding materials with improved nutrient uptake, simple diagnosis of nutrient conditions of soil, and smart management of fertilizer depending on specific soil and environmental conditions) and the examination of these intergradations for stable rice production in SSA (Fig. 1). Moreover, we have developed technologies to improve the efficiency of water use by minimizing the loss of water in the system of rice irrigation, aiming to expand the irrigated area. Furthermore, we evaluated the impact of the developed technology in the region and elucidated the conditions for its dissemination. We focus on nutrition deficiency and water shortage problems in rice cultivation and describe both the status of research and our efforts.

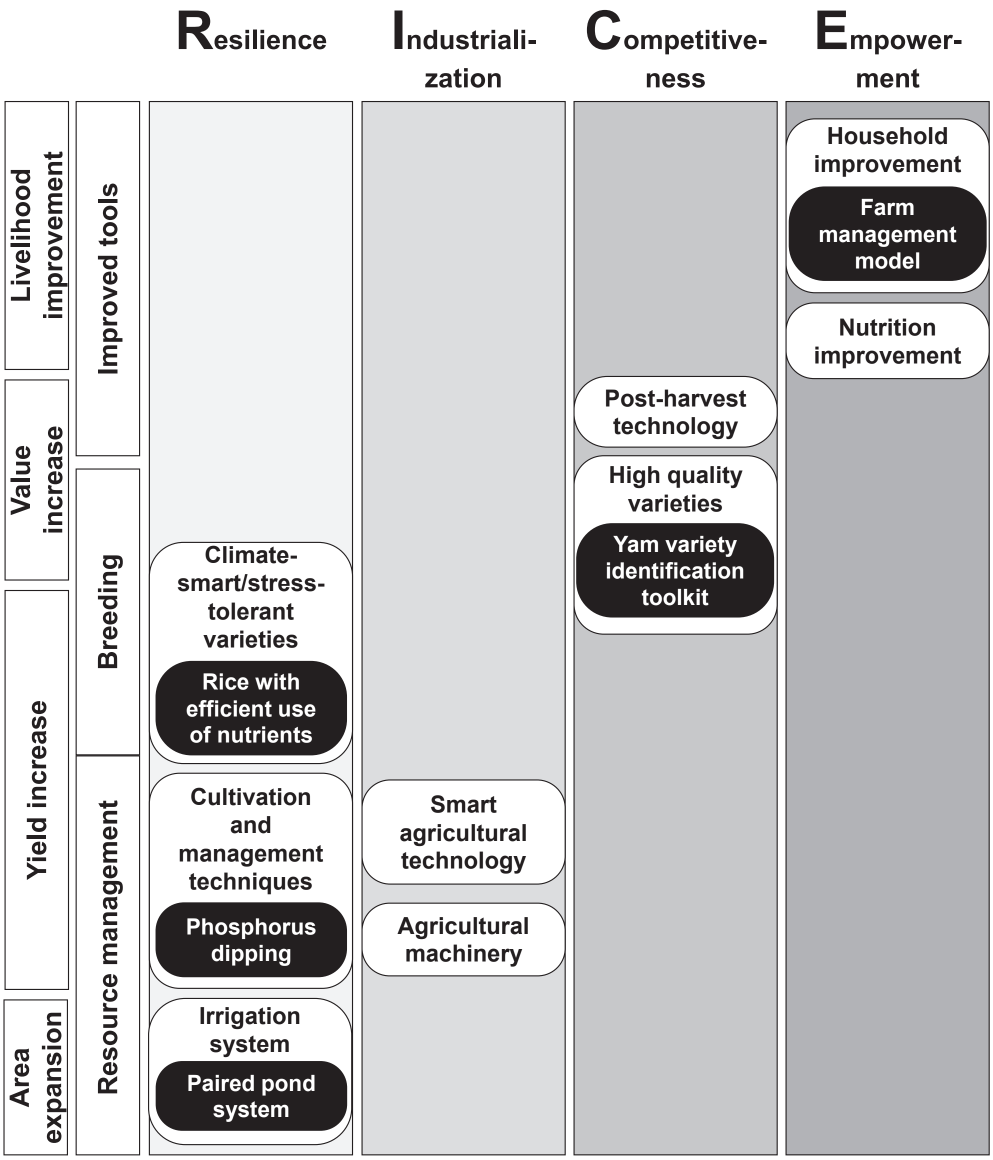

Fig. 1. RICE approach for CARD2 and its analogy to representative research activities under the Food Security in Africa project of JIRCAS
Black ovals show key findings of the Food Security in Africa project.

1. Challenges caused by deficiencies in nutrients such as nitrogen (N) and phosphorus (P)

Changes in rice grain yield and mineral N input in Southeast Asia and SSA from 1961 to 2019 (FAOSTAT 2020) indicate that the rate of N application in Southeast Asia has increased 20-fold since 1971, from 5 to 105 kg N ha^{-1}, during which time the region had significantly increased rice yields (Tsujimoto et al. 2019). In contrast, the rate of N application of SSA until recently remained < 10 kg N ha^{-1}, in accordance with consistently low rice yield levels. Alternatively, in SSA, the amount of fertilizer use is insufficient, and the soil is undernourished for rice, which is a problem that small-scale farmers face during rice production. Improving the N use efficiency (NUE) by using rice varieties with high NUE and fertilization techniques is important for improving crop yields and reducing the demand for N fertilizers. Reducing pollution in the global environment is also important, as indicated by the biogeochemical flow of N at planetary boundaries (Rockström et al. 2009).

Rice varieties with high NUE can reduce the amount of fertilizer required for sustainable agriculture. However, plant NUE is inherently complex because it involves N sensing, uptake, translocation, assimilation, and remobilization and is governed by multiple interacting genetic and environmental factors (Fan et al. 2017, Krapp 2015, Xu et al. 2012). Enhanced N acquisition must be accompanied by efficient transport and assimilation to promote growth and development, ultimately increasing yields. Tang et al. (2019) reported that a genome-wide association study identified NAC42-activated nitrate transporters that confer high NUE in rice. Chen et al. (2020) succeeded in improving NUE by manipulating nitrate remobilization in plants, including rice. Yoon et al. (2020) reported that transgenic rice overexpressing Rubisco exhibited increased yields with improved NUE in an experimental paddy field. Increasing knowledge of genes and interactions associated with these critical processes will accelerate the development of new rice varieties with higher NUE.

Field-specific fertilization is key to improving the NUE of rice growing in SSA soils with heterogeneous and low nutrients (Tsujimoto et al. 2019). NUE shows large spatial variation even in small areas, and it can be improved by coping with the spatial variation of soil-related factors, including deficiency of minor elements such as sulfur and toxicity of iron (Fe). NUE is also affected by dynamic changes in hydrology and soil characteristics. However, recent technological advances, such as unmanned aerial vehicles that capture microtopography at low cost, a database of high-resolution soil nutrient characteristics, and interactive decision support tools using on-site smartphones, have created opportunities to integrate these microtopography and soil-related variables into field-specific fertilizer management. The development of breeding materials with improved NUE using locally adapted varieties has also been effective at stabilizing rice production in SSA.

P deficiency is one of the main constraints in the production of rice (Saito et al. 2019, Tanaka et al. 2015, Vandamme et al. 2016). P deficiency in SSA is associated with highly weathered tropical soils, low biologically available P content, and P-harboring capacity associated with acidity and the abundance of Fe and aluminum (Al) oxides (Batjes 2012, Bekunda et al. 2010, Kawamura et al. 2019, Nishigaki et al. 2019). Insufficient application of P because of the limited purchasing capacity of smallholders is another important issue associated with shortages of P in SSA. Agriculture in SSA generally has lower fertilizer inputs, and application of P fertilizer is even lower than that in the other parts of the developing world (Nziguheba et al. 2016). The biogeochemical flow of P is one of the most serious problems in planetary boundaries (Rockström et al. 2009). Alewell et al. (2020) reported that a global shortage of P will be aggravated by soil erosion, and Africa, which cannot afford the high cost of fertilizers, is one of the areas with the highest rates of P depletion. In the future, with an assumed absolute shortage of mineral P fertilizer, the agricultural soils available worldwide will be depleted. Under these constraints, it is essential for smallholders in SSA to use rice varieties with improved P utilization efficiency (PUE) and find effective practices for management of P fertilizer for crop production to achieve increased yields per unit of applied P fertilizer. In addition, a P recycling system is recommended for sustainable agriculture.

The development of breeding materials with improved PUE using locally adapted varieties is effective at stabilizing rice production in SSA. To access P in the soil, plants have the ability to evolve high- and low-affinity P transporters and induce structural changes in the roots to forage P (Heuer et al. 2017). Of the many genes associated with crop P deficiency, genes such as *phosphorus starvation tolerance 1* (*OsPSTOL1*) encoding a protein kinase, *Arabidopsis vacuolar proton pyrophosphatase 1* (*AVP1*) encoding a proton-pyrophosphatase, *PHOSPHATE 1* (*PHO1*) encoding a *SPX-EXS domain protein*, and *phosphate transporter 1;6* (*OsPHT1;6*) encoding a phosphate transporter are expected to increase the PUE of P fertilizers in agricultural systems. However, it has been noted that combining PUE with resistance to other stresses, such as Al toxicity, is important. Our group selected lines with a high yield and short growth period, possessing *phosphorus uptake 1*

(*Pup1*) (Gamuyao et al. 2012), a quantitative trait locus (QTL) for phosphate deficiency tolerance, including *PISTOL1*, in the fields of Madagascar, which is one of the major rice-producing countries in Africa and one of the countries with the shortest life expectancy and lowest income (Gapminder 2020). Selection was performed in collaboration with the National Center for Applied Research on Rural Development (FOFIFA), Madagascar. We have also started an adaptation test for a variety of registrations.

A joint research collaboration between JIRCAS and FOFIFA has shown that P-dipping treatment of seedlings, called "P-dipping," can significantly improve the efficiency of fertilizer use and yield of rice (Rakotoarisoa et al. 2020). In this technology, rice seedlings are dipped in a mud-like mixture of P fertilizer and paddy soil before transplanting. On-farm field trials in Madagascar have clarified that P-dipping shortens the number of days from transplanting to maturity and avoids cold stress during the reproductive stage. In addition, P-dipping increased the yield by 9%-35% compared with the conventional method of fertilizer broadcasting. In SSA, including Madagascar, the productivity of rice is severely limited due to the poor supply of nutrients such as P and the unstable production environment because of water shortage, low temperature, and high temperature stress during the cultivation period. The dissemination of this technology is expected to contribute to improved and stable rice production in SSA and further enhance food security in the region.

2. Water shortage challenges in rice agriculture

Rice is highly sensitive to stresses, such as dehydration, from the panicle formation stage to the flowering stage. However, in the SSA savanna, which has a dry season, people often cannot obtain enough water due to an unstable precipitation pattern during this period in the cropping cycle. Droughts frequently occur globally, including in Africa, and in the past, many crops, including rice, have been severely damaged (Kim et al. 2019). Due to recent climate change, extreme weather events frequently occur worldwide. Africa is no exception, and there are concerns that precipitation patterns will become more unstable because of forecasted global climate change. Under a joint project between Kenya and Japan, the development of rice varieties carrying useful genes/QTLs to overcome biological and abiotic stresses, including drought in Kenya, has been promoted (Makihara et al. 2018). These include different root developmental traits associated with drought avoidance in the two New Rice for Africa (NERICA) varieties—NERICA1 and NERICA4—and the desirable root traits for upland rice cultivation vary depending on the target soil environment, such as the distribution of soil moisture and root penetration resistance (Menge et al. 2016). Genetic improvement studies have been conducted to withstand drought-sensitive periods to ensure rice yields. The *DEEPER ROOTING 1* gene, which regulates the root angle to obtain water from deep soil, was discovered and used to improve the yield of shallow rooting rice under drought conditions (Uga et al. 2013). Our group has also promoted the production of a drought-tolerant rice strain developed using biotechnology, including the modification of genes (Selvaraj et al. 2017) and the development of long-rooted rice using marker-assisted selection (Obara et al. 2014). Yadav et al. (2019) reported a QTL that contributes to rice grain yield under reproductive stage drought stress, which was identified based on genotyping-by-sequencing mapping. The identified genomic regions can be used in breeding programs. Furthermore, agricultural engineering measures, such as irrigation systems, are expected to be effective. To stabilize rice yield in the SSA savanna, supplementary irrigation is particularly effective during the reproductive period when rice is vulnerable to water shortage; thus, the development of a supplementary irrigation technology for rice suitable for the SSA savanna is required.

We have developed a supplementary irrigation system for rice production using the "paired pond system" in northern Ghana. This system saves water overflow by channeling it from an existing reservoir (dugout) into a new small reservoir, enabling the utilization of water for supplementary irrigation during the critical period to ensure rice seed fertility in paddy fields. JIRCAS (2017) has published a manual based on the results of this study. Furthermore, we monitored farmers using the system and conducted an impact assessment and factor analysis of farmers' acceptance of the newly developed technologies. We also created a farming planning model that reflected management conditions, water usage conditions, and social conditions for irrigated rice farmers based on the farm management model developed in Mozambique (see item 3, crop–livestock integration). The model elucidated the effects of irrigated rice technologies (Koide et al. 2021) on increasing and stabilizing farmers' incomes. We hope that this system will contribute to cultivation of rice, especially in the savanna zone.

Through scientific recommendations and the dissemination of the research results, the technologies and breeding materials developed in this project contribute to CARD Phase 2, which started in 2019 with the goal of "doubling rice production by 2030" (Coalition for African Rice Development 2020) (Fig. 1). Rice self-sufficiency in SSA is insufficient, and a large part of the region is dependent on imports. In view of the changes in the global food chain system driven by climate change and the new coronavirus disease 2019 (COVID-19), we estimate that research support for improving the rice production capacity of SSA will become more important.

"Regional crop utilization" project

Crops that are important in a particular area but have not been improved sufficiently regarding breeding and production techniques are called "orphan crops" (also referred to as "minor crops," "underutilized plant species," "neglected crops," and "future foods") (Tadele 2019, Jamnadass et al. 2020). One approach to crop diversification to support human nutrition in Africa is the promotion of African orphan crops rich in vitamins, essential minerals, and other micronutrients important for healthy diets (Jamnadass et al. 2020). Yams and cowpeas are regionally important crops that can alleviate widespread poverty and hunger in West Africa through their economic and nutritional values and a deep linkage with the peoples' lives and culture fostered by a long history of cultivation. However, research on these two crops has been hindered because of low scientific attention and technical difficulties compared with major crops, such as rice, maize, wheat, and soybean, and even with other African crops that have wider cultivation around the world, such as cassava, sweet potato, common beans, and groundnut. In particular, these two crops are lacking in terms of the information and techniques required for effective breeding in both genotyping and phenotyping. Recent advances in genomics research and phenotyping technology have laid the groundwork for the genetic improvement of orphan crops (Tadele 2019, Jamnadass et al. 2020). For example, the genome sequence of quinoa (*Chenopodium quinoa*), a regionally important crop in Latin America, has been elucidated (Jarvis et al. 2017, Yasui et al. 2016), paving the way for molecular breeding. However, owing to their high regional characteristics, these regional crops have received limited research attention despite having great potential for improvement in both productivity and quality.

Yams are widely cultivated as a staple food in Africa, and approximately 95% (54 million tons) of the world's production is produced in the Guinea Bay area of West Africa called the "Yam Belt." In particular, Guinea yam is an important staple food crop that is indispensable to the diet of the region and is a major cash crop for farmers. However, the target of use is underground tubers, making cultivation tests and surveys difficult to conduct over time. Furthermore, the fact that males and females differ depending on the variety and lineage and that sex cannot be determined without flowering has been a major obstacle to efficient breeding. In addition, cowpea, a traditional African legume, is a source of cash income for farmers and an important source of protein and micronutrients, and its production in West Africa accounts for over 80% of world production (FAOSTAT 2020). Therefore, in recent years, it has been noted that in addition to improving the yield and pest resistance, which are conventional breeding targets, developing new varieties to improve the quality and nutritional value of grains is important. In particular, as protein is an indispensable element for growth in humans, the grain protein content of cowpea is an important trait when considering the development of varieties suitable for the region. However, research on cowpea, whose production in the world is centered mostly in West Africa, is limited. The breeding of yam and cowpea varieties, which are highly productive, show stable production even in poor environments, and have excellent nutrition and palatability, is an important solution for securing a balanced diet and income sources for smallholders in Africa. The development of genotyping and phenotyping technologies is expected to accelerate the breeding of these crops. In particular, we could meet various demands of the people that are deeply linked to local culture and traditions through the utilization of diverse genetic resources that are not fully exploited. Aiming toward the active utilization of the rich genetic diversity of both crops through international and national breeding programs, the project focused on the accumulation of fundamental information on their genetic diversities and the development of effective tools to enable breeders to select and evaluate their materials using this information. This study was conducted in Nigeria and Burkina Faso, with strong collaboration with the International Institute of Tropical Agriculture (IITA), which holds rich genetic resources of cowpea and yam and conducts breeding programs, and the Institut de l'Environnement et Recherches Agricoles. In addition to our efforts to release the genetic diversity data through the open-access EDITS-Cowpea database (JIRCAS 2016) and Yam base (JIRCAS 2020) to enhance the utilization of diverse genetic resources of the crops, effective tools and information have been developed as summarized below.

1. Challenges in developing genotyping technology to accelerate the breeding of yam and cowpea

To improve the efficiency of yam breeding, we conducted international joint research with IITA and other institutions on the development of scientific information and technological development that forms the basis of yam agriculture. To enable breeding based on the genetic profile of the yam, Tamiru et al. (2017) succeeded in decoding the genome sequence of Guinea yam. We also identified loci that determine sex based on genomic information and developed a DNA marker that enables sex estimation at the seedling stage. In normal cultivation, it takes 2-3 years to reliably determine sex, and the use of the marker developed by us would allow the selection of varieties and lines with excellent properties as breeding parents without waiting for flowering in the seedling stage. Together with *D. rotundata* Diversity Research Set, smaller set (102) of accession of Guinea yam, selected by us for the effective use of these advanced technologies in yam research (Pachakkil et al. 2021), it is expected that the breeding efficiency of Guinea yam can be improved, such as the number of individuals handled in the trial cultivation and the field area can be reduced.

At the sites of breeding of yam and production of its seedlings, identifying varieties from only the aboveground parts of the plant and the appearance of tubers is very difficult. Therefore, mixing other varieties and lines in each process of planting, cultivating, harvesting, and preserving has been a problem for many years. Therefore, we have developed a yam variety identification technology package that can be easily and quickly used in the field by breeding programs, seed companies, and extension organizations. We have also succeeded in providing a toolkit to support the use of DNA (simple sequence repeat) markers reported by Tamiru et al. (2015), the web application to select suitable and minimum combinations of DNA markers, and databases containing polymorphism data of over 500 genotypes (JIRCAS 2020). We can contribute toward improving the efficiency and quality of breeding and seedling production using the developed variety identification technology for the confirmation of mating parents, prevention of contamination with other varieties and lines in each cultivation process, and dissemination and sale of quality assured seedlings.

Recently, an international consortium has deciphered the genome information of cowpea (Lonardi et al. 2019). It is expected that this genomic information will be used in genotyping technology to accelerate cowpea breeding.

2. Challenges in developing phenotyping technology to accelerate the breeding of yam and cowpea

The field of genomic research on crops has made great strides, and the genome sequences of many crops have been recently deciphered, thereby facilitating genotyping analysis. However, phenotyping technology, which evaluates crop performance in the field, has become a bottleneck for improving breeding efficiency, and thus is a focal point of research to increase efficiency and speed up the development. Thus far, developed countries have been developing phenotyping technology for large-scale greenhouses and fields of major crops as well as have developed high-speed phenotyping technology for use in fields (Yang et al. 2020). However, the development of phenotyping techniques for orphan crops, such as yams and cowpeas, which are mainly produced in Africa, is inadequate. In addition, the development of high-speed phenotyping technology for traits related to nutrition and quality, such as protein content in cowpea seeds, is required to accelerate breeding.

Iseki & Matsumoto (2018) developed a simple and inexpensive method for the nondestructive estimation of the aboveground biomass of yams cultivated in pillars. The normalized difference vegetation index (which represents the amount and activity of vegetation) for each individual can be obtained by installing a plate behind the yam plant that is cultivated on a support and scanning a small spectroscopic reflection measuring instrument along the support rod in parallel with the plant. Therefore, not only can the growth survey of yams be significantly reduced, but it can also be used as a growth diagnosis index in farm fields.

Stomata conductivity (stomatal conductance) is an index that shows the ease of passage of water vapor and carbon dioxide in the stomata. It is widely used in all fields as an index of crop photosynthetic ability and resistance to environmental stress such as drought; however, there are problems such as inconsistencies induced by the measurement environment. Iseki & Olaleye (2019) developed a new index for estimating stomatal conductivity using leaf surface temperature obtained from the thermal images of cowpea plants. This new index, which is based on a mathematical model, is less affected by the measurement environment compared with the conventional index. Therefore, it could be widely used for evaluating the tolerance to drought stress and the photosynthetic activity of crops in fluctuating environments.

Furthermore, we focused on the protein content, which is an important quality-related trait of cowpea grains, and developed an evaluation technique that can be used for selecting promising strains and rapidly evaluating the effects of the cultivation environment. Muranaka et al. (2015, 2016) succeeded in estimating the N content of a powder sample of cowpea grains using infrared light and converted this into protein content. Subsequently, Ishikawa et al. (2017) succeeded in developing a technique for the nondestructive estimation of the N content of whole intact cowpea grains using near-infrared spectroscopy and converted this into protein content. The use of these techniques allows for the rapid assessment of the grain protein content available during the breeding process.

We hope that these technologies will contribute to the acceleration of yam and cowpea breeding in West Africa and the improvement of local nutritionally balanced diets and households.

"Crop–livestock integration" project

Agriculture is a major sector that drives the economic growth in many SSA countries. In most countries in Eastern and Southern Africa, beef and milk are among the top five products based on production value. This indicates that livestock farming is important to not only provide protein as an essential nutrient for the human body but also to improve farmers' incomes. The main constraint in livestock production in African savanna dairy farms is feed shortages, in terms of both quantity and quality (Antonio et al. 1991). Dairy farmers, including small-scale farmers, face regular feed shortages during the dry season, as the dry season lasts for > 6 months each year. Traditional animal husbandry practices in countries such as Mozambique consist of simple grazing on native grasslands, with by-products of crops used as supplements. However, this feeding pattern does not meet the nutritional requirements of dairy cows, and the poor quality of roughage results in poor milk yield and quality (Wiedmeier et al. 2002). To improve the household nutrition of local small-scale farmers by promoting dairy farming, developing a high-quality feed suitable for the local area throughout the year and stable feed in the dry season is necessary.

In Mozambique, one of the countries with short life expectancy and low income (Gapminder 2020), there is a strong desire to restore the livestock industry that collapsed because of the civil war from 1977 to 1992. The promotion of dairy farming is expected to make a significant contribution to improving the nutrition of the local people. We sought to improve food and nutrition security in this country through a crop–livestock integration system to reduce the dependence on feed imports by using by-products generated during crop production and food processing for the livestock industry and waste such as livestock manure in crop cultivation to maintain soil fertility. In this project, we developed an effective and efficient integrated crop–livestock system applicable throughout the year in collaboration with the Agricultural Research Institute of Mozambique to increase dairy production in tropical savanna areas, which have distinct rainy and dry seasons.

The utilization of silage from the residue of agricultural products harvested during the rainy season to ameliorate cattle food shortages during the dry season and fermented total mixed ration (TMR) using locally available agricultural by-products for the stable supply of cattle food throughout the years are effective to ameliorate cattle food shortages during the dry season. Two crop by-products, corn stover and sugarcane top, contain certain crude protein and neutral detergent fiber nutrients that can be well preserved in silage (Cai et al. 2020). The fermented TMR prepared with local feed resources has helped attain good quality and improved milk yield in dairy cattle in Mozambique (Du et al. 2020). The nutritional values of other local feed resources, including native grasses, were analyzed to develop a feeding plan for dairy cattle. The productivity of food and feed multipurpose crops, such as cowpea and sweet potato, affected by soil water and fertility status, has been examined. We have also used waste from livestock farming as a soil fertility management method by farmers to improve food crop production and sustain forage crop production.

By integrating these technologies, we can propose an integrated crop–livestock model for dairy farmers in Mozambique through researchers and extension workers. The integrated model is evaluated by the farm management model, which can facilitate technology adoption by African smallholders and livelihood improvement. Using farming conditions and indexes, conditions for subsistence, and nonfarm activities as inputs, the model computes (by linear programming) the optimal farming plan to maximize the total income while growing enough food for home consumption using mixed cropping and intercropping for risk dispersion and ensuring nonfarm income and labor allocation. Koide et al. (2018a, 2018b) and JIRCAS (2019b) applied the model to the Nacala Corridor, northern Mozambique, and identified the optimal crop combinations and income increases according to the agroecological zones and farming scales. Upgrading this model, Koide & Tinga (2021) developed a complex management planning model for small-scale farmers in southern Mozambique to achieve efficient crop–livestock integration with dairy farming. We hope that these technologies will contribute to the promotion of livestock production in Mozambique and the improvement in nutrition in the region by expanding milk production.

Future prospects

In CARD2, the efforts that should be especially noted are organized as the "RICE approach," an acronym formed from the first alphabet of four keywords (Coalition for African Rice Development 2020, Maruo 2018):

R: Resilience will handle adaptation to climate change through seed breeding, dissemination, and irrigation development.

I: Industrialization will address the issues of mechanization, access to local and regional markets, and support for private sector involvement and investment.

C: Competitiveness will include the dissemination of certified seeds and the improvement of postharvest technologies.

E: Empowerment will deal with improving household incomes and livelihoods and access to finance for smallholder farmers, most of whom are women.

We believe that these approaches are equally important not only for rice but also for other crops and agricultural industries, including yams, cowpeas, and livestock (Fig. 1).

In the future, for food and nutrition security of small-scale farmers in SSA, we should use not only the technologies already developed in other regions but also big data, Internet of Things, artificial intelligence, and cyber-physical systems, which have been rapidly advancing in recent years. We must develop sustainable technologies and varieties that can improve productivity in SSA while preserving the environment, such as the following:

1. Resilience

- Development of varieties suitable for the environment and responding to climate change using genome breeding, genome editing, and phenotyping technology
- Establishment of a cropping system that maximizes the potential of crops considering genotype (G) × environment (E) × management (M), with the management of resources such as soil, water, and fertilizers for sustainable agricultural production
- Selection of farmland and development of irrigation facilities in consideration of climate change

2. Industrialization

- Development of smart agricultural technology suitable for SSA
- Utilization of smart agricultural machinery suitable for SSA

3. Competitiveness

- Utilization and breeding of various foods, including orphan crops, for nutrition improvement
- Development of technologies and varieties that contribute to value addition in the food value chain not only in production but in processing, distribution, and consumption

4. Empowerment

- Farmer-based or farmer-centered approaches for the improvement of livelihood and nutrition

In addition, developing partnerships with related research institutes and human resource development in SSA that can autonomously promote research is important.

Many stakeholders need to work together to achieve food security in Africa. We are working on the development of suitable varieties and technologies with not only our counterparts in local research institutes but also in the field, together with farmers who are the users of the research products and participate in the early stages of testing. To achieve SDG Goal 1 (Poverty Eradication) and Goal 2 (Zero Hunger) by 2030, stakeholders, such as public research institutes, academia, and the private sector, need to work together. Because the current dissemination system in Africa is fragile, actively working on smart technologies, such as smartphone apps, which have been rapidly developed in recent years, is necessary to widely disseminate the developed techniques and varieties.

Recently, the World Food Programme estimated that > 2.5 billion people will suffer from acute hunger due to the COVID-19 pandemic by the end of 2020 (World Food Programme Insight 2020). Good nutrition is an essential part of an individual’s defense against COVID-19, and nutritional resilience is a key element of a society’s readiness to combat the threat (Development Initiatives 2020). There is concern that the global food and nutrition security crisis will worsen in addition to the social and humanitarian crisis due to the spread of the infection to vulnerable low-income developing regions, including SSA. Efforts to stabilize food production and resolve malnutrition are increasingly important. Global transformation of the food system is urgently needed as many of the world’s populations face nutritional problems and many environmental systems and processes have crossed over the safe boundaries for our planet (Willett et al. 2019). To establish a sustainable agricultural system, we need to develop technologies that are readily available and effective and lead to an increased food productivity for farmers by integrating biological and ecological processes into food production without adversely affecting the environment (Pretty 2008). By promoting the dissemination of the developed technologies and maximizing research outputs, we shall contribute to improving both the productivity and nutrition of agricultural products in developing regions, especially in SSA, and eradicating poverty and creating a peaceful and healthy society.

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