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Review

Improvement of Rice Production under Drought Conditions in West Africa: Application of QTLs in Breeding for Drought Resistance

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Abstract: Rice plays a paramount role in food and nutrition security in many West African countries. Despite the doubling of production during the last decade, rice consumption has grown faster, creating a deficit between the demand and supply. Although the West African sub-region remains the main rice-producing centre on the continent, production is severely hampered by biotic and abiotic stresses. Drought is one of the factors that most severely reduce grain yields of rice. Systems of production need to be established in order to mitigate yield loss as a result of drought. This review discusses the effects of drought on rice production in West Africa and its mitigation with an emphasis on the improvement of tolerance to drought stress. Yield stability can be achieved by developing drought-tolerant varieties through several processes encompassing profiling of known QTLs and identification of new ones, marker-assisted selection, genomic selection, and extensive multi-locational yield trials. We suggest a comprehensive strategy for breeding drought-tolerant rice varieties in West Africa.

Key words: West Africa; rice; drought-tolerant variety; QTL; high-throughput genotyping

Rice (*Oryza sativa*) is one of the most important crops in the world. Worldwide, the total area under rice cultivation is around 1.58 × 10^8 hm^2 with a total production of more than 7.0 × 10^8 t/year, accounting for 4.7 × 10^8 t milled rice (Prasad et al, 2017; FAOSTAT, 2021). Africa accounts for 3.5% of the total worldwide rice production, with Sub-Saharan Africa producing a total production of over 1.9 × 10^7 t, accounting for more than 50% of African production in 2019 (FAOSTAT, 2021). In Sub-Saharan Africa, rice is generally grown on small farms of 0.5 to 3.0 hm^2 in size.

Rice as one of the main staple foods supplies the largest quantity of calories for African (Mohanty et al, 2013). In many African countries, rice has overtaken other staple foods because of the ease in preparation and digestion. Rice production has grown fast in Africa, but its consumption has grown even more rapidly (https://www.africarice.org/sustainable-productivity). West Africa is the main rice producing sub-region in Africa, with Nigeria as the leading producer. In terms of rice production by the individual countries in 2019, the three leading producers in Africa are Nigeria (8 ×

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10^6 t with approximately 5.0×10^6 hm^2 harvested area), Egypt (6×10^6 t with approximately 7.8×10^5 hm^2) and Madagascar (4×10^6 t with approximately 8.2×10^5 hm^2) (FAOSTAT, 2021).

Despite the vital role of rice in the livelihoods of the West African people, its production is greatly threatened by climate related stresses, notably drought. Drought represents the most important abiotic constraint that hampers rice production, and contributes to yield instability in Sub-Saharan Africa (Lanceras et al, 2004). With the current patterns in climate change, culminating in extreme events, water scarcity and drought, deficits in water potential and turgor of the plant are particularly expected to be frequent in the near future (Wassmann et al, 2009; Lisar et al, 2012). Water plays a major role in agriculture and food production (Wang et al, 2012), and its deficit threatens food security by reducing crop yields and increasing the year-to-year variability (Foley et al, 2011).

Understanding the genetic basis of drought stress tolerance in rice will boost the development of new varieties with improved grain yields under such conditions. To this end, the identification of QTLs for grain yield under drought conditions is an important step towards the development of drought tolerant varieties. The most useful QTLs for successful breeding are those with large and consistent effects across various genetic backgrounds and environments (Yadav et al, 2019). There is the need for plant breeders to use such QTL to develop climate smart rice varieties to help bridge the gap between rice production and the ever-increasing consumption demands in West Africa.

Africa Rice Center (AfricaRice) has developed NERICA (New Rice for Africa) varieties, which combine the stress tolerant attributes (weed competitiveness, resistance to iron toxicity, waterlogging, nematodes, major African rice diseases and pests, tolerance to drought, acid soils and low phosphorus) of *O. glaberrima* with the high-yielding potential of *O. sativa* (Prasad et al, 2017). Considering the imminent worsening climatic conditions especially drought, more efforts are needed to diligently develop new high-yielding and drought-tolerant varieties that also have good grain quality attributes.

To successfully introduce such rice varieties in West Africa, breeding programmes should tackle the problem from a multidisciplinary approach. The multidisciplinary strategy should include efficient methods, including combined selection of drought tolerant traits with other stresses and use of molecular techniques including integrated omics approach to candidate genes with a major regulatory role in drought tolerance expression (Sahebi et al, 2018).

The use of high-throughput phenotyping platforms for rapid and precise phenotyping, physiology and eco-physiology, bioinformatics and biostatistics will be useful to understand physiological traits and make breeding for commercially viable, climate-resilient rice varieties more efficient.

In this review, we discussed the effects of drought stress on rice productivity in West Africa, and mitigating strategies to overcome the effects of drought on yields with a focus on the development of drought tolerant rice varieties. We also highlighted some QTLs for their use in breeding for drought tolerance in rice. Finally, we proposed a comprehensive strategy to take into account for the breeding and development of climate-resilient crops for West Africa with a particular emphasis on rice. Even though we emphasised on the use of QTLs for drought tolerance from classical biparental mapping, we made mention of genome-wide association study (GWAS), genomic selection (GS) and CRISPR/Cas9 as tools that can be used to increase genetic gain.

Impact of drought on West African agriculture

Drought stress is one of the numerous critical issues influencing agricultural production in Africa. One-third of Africa's population are vulnerable to the impacts of droughts as they live in drought prone areas. Based on FAO statistics, drought induced crop losses amounted to 19.3 billion US dollars, while livestock losses were estimated at 4.2 billion US dollars within a decade (between 2003 and 2013) in Africa (FAO, 2015). The Sahel region is the most affected by drought in West Africa with severe impacts on food security and sovereignty (Bates et al, 2008). Rural communities are extremely vulnerable to frequent disasters resulting from poverty, increasing population, difficulties in accessing the basic services and poor investments in agriculture. When drought, flood and pest occur, they suffer a direct impact of food and nutrition security as they mainly depend on agriculture and pastoralism for their livelihoods. In addition to the several constraints including diseases, pests, poor soil fertility and limited access to improved seeds and inputs, the situation of farmers and pastoralists in West Africa is worsened by prolonged drought (Stige et al, 2006; Bates et al, 2008).

West Africa is characterised by meteorological and agricultural droughts (Kasei et al, 2009; Quenum et al, 2019), which are our focus in this review. Since the severe drought of the 1970s, agricultural drought in West Africa has been characterised by longer dry spells and seasonal drought.

Drought and temperature stresses are predicted to worsen to critical levels in tropical and subtropical regions, although the trend and severity will vary among countries. Most of the severe global drought occurrences in the last decade had been in Africa, where the globally lowest levels of crop production and drought adaptive capacity exist (Bates et al, 2008). Drought has adversely affected crop productivity in different parts of the continent, and it has a severe effect on rice production in many parts of West Africa (Bates et al, 2008). As predicted by global climate models, recurring drought events under future climate change may result in increasing crop failures by 4.5 times more in 2030 and 25 times more by 2050 across major agricultural regions in the world (Caparas et al, 2021), if drought would occur during sensitive stages of crop growth.

Impact of drought on rice production systems in West Africa

Drought affects 33% of potential rice production area in Africa, followed by iron toxicity (12%), cold stress (7%) and salinity stress (2%) according to the mapping of abiotic stress study for rice in Africa conducted by van Oort (2018). Based on the analysis of the soil water-holding capacity, Haefele et al (2014) revealed that drought represents 19% of constraint for all rice production area across Africa, coming only after low soil fertility (37.6%). About 40% of the overall area under rice cultivation in Africa is upland ecology, 38% for rainfed lowland, 12% for irrigated lowland, 6% for deep water and floating rice, and 4% for mangrove swamps. Thus, rainfed lowland and upland rice production which are prone to drought stress occupy about 80% of the overall rice production area in Africa (Bimpong et al, 2011).

In West Africa, there are three major rice production systems namely irrigated, upland and rainfed lowland systems. Rainfed lowland production covers 40% of the total area, followed by irrigated area of 11.6% and the upland rice system occupies 43% (RICOWAS, 2021). Rainfed lowland and irrigated production systems are the most productive (RICOWAS, 2021), but their vulnerability to the incidence and severity of drought and crop failure are expected to worsen with climate change (Bimpong et al, 2011). Drought stress is more severe in north of 10 ºN and less in south of 10 ºN in West Africa (van Oort, 2018). Longer dry spells and seasonal drought are expected to increase in West Africa.

In Sub-Saharan Africa, rice self-sufficiency became worse in 10 years between 2008 and 2018, moving from 63% to 59% in 23 member countries of the Coalition for African Rice Development (CARD) due to the increased demand for rice consumption, even though rice production doubled during that period (Arouna et al, 2021; Futakuchi and Saito, 2021). The increase in rice production in Sub-Saharan Africa between 2008 and 2018 was mainly as a result of area expansion in an extensive agricultural production system rather than by yield increase (Arouna et al, 2021; Futakuchi and Saito, 2021). Moderate increases of West African rice production and harvested area were recorded from 2008 to 2015, while a rapid increase of rice harvested area as compared to the rice production was observed from 2016 to 2018. Yields were increased from 2.17 to 2.36 t/hm^2 during 2008 to 2018 in CARD countries, constituting close to 9% increase. About 12% of yield increase to 2.43 t/hm^2 was observed after the food crisis of 2008–2010, followed by a decrease to 2.26 t/hm^2 in 2011, but from 2012 to date, rice yield has been wavering around 2.35 t/hm^2. The yield decrease recorded in 2011 is partly due to bad weather conditions such as flood and drought occurred across Africa (https://www.africarice.org/sustainable-productivity). By 2019, the total rice production in West Africa had reached 2×10^7 t for the first time in history, while the harvested area was decreased by 713 241 hm^2 as compared to 2018 (FAOSTAT, 2021). Efforts are therefore needed to keep the production increasing despite the predicted future drought.

Over the last three decades, nearly 53% of rice harvesting regions experienced the influence of climate variability on rice yield at the rate of about 0.1 t/hm^2 per year and 32% to 39% of rice yield variability is due to year-to-year climate variability (Ray et al, 2015). Drought has a significant adverse effect on the livelihood of rainfed lowland rice producers due to its unpredictable occurrence as a result of the current changes in climate (Serraj et al, 2009). Projections indicate that by 2080, the proportion of arid to semi-arid areas in Africa will increase from 6% to 8% (Jarvis et al, 2010). If nothing is done, significant proportions of West African farmlands would become non-arable with a serious impact on agricultural productivity (Ndjiondjop et al, 2018).

Rice's vulnerability to drought stress during various stages of its growth is well documented. The major impact of drought stress occurs at the flowering and grain filling stages, leading to critical grain yield and quality losses. Singh et al (2010) observed reductions in many traits including grain yield under drought conditions. Yield decreases are attributable to the detrimental effect of drought on plant height, tiller number, panicle number, leaf area, root length, root depth and thickness, panicle exertion, spikelet fertility, leaf greenness and temperature, days to flowering and maturity, leaf rolling and leaf tip drying (Bocco et al, 2012; Ndjiondjop et al, 2012). Grain yield is reduced by drought through the shortening of the grain filling period (Shahryari et al, 2008), disrupting leaf gas exchange properties, limiting the size of the source and sink tissues, impairing phloem loading and assimilate translocation (Farooq et al, 2009).

Drought mitigation and adaptation strategies in rice production systems in West Africa

Irrigated rice yields during wet season in West Africa are projected to decrease by 21% without adaptation measures and increase by 7% with adaptation (van Oort and Zwart, 2018). On the other hand, dry season irrigated rice yields will decrease by 45% without adaptation and 15% with adaptation (van Oort and Zwart, 2018). To mitigate the negative impact of climate change on rice production, various adaptation measures have been adopted in African, namely, the continuous improvement methods and tools developed by the Excellence in Breeding Platform to improve breeding schemes and develop varieties that are adapted to current climatic conditions (Covarrubias-Pazaran et al, 2022), successful use of alternate wetting and drying in Senegal (Djaman et al, 2018), Burkina Faso (Akpoti et al, 2021) and Ghana (http://recirculate.global/wp3/disseminating-awd-to-rice-farmers-in-ghana/), use of mycorrhizal fungi to optimise water-saving alternate wetting and drying technique in rice cultivation in West Africa (Ndoye et al, 2022), selection of cultivars with stress escape or avoidance attributes (http://irri.org/our-work/research/better-rice-varieties/climate-change-ready-rice), and breeding for drought tolerant rice varieties (AfricaRice, 2008; Afiukwa et al, 2016). Even though the combination of different adaptation and mitigation measures gives better results and is recommended, West African farmers do not have the skills and the means to always afford all the items necessary to carry out these measures simultaneously. In West Africa, it appears that the most appropriate method to mitigate the dramatic effect of drought on rice yield is the use of drought tolerant varieties, since it is easily manageable and affordable to farmers.

AfricaRice has initiated a project named Genetic Diversity and Improvement (GDI) Programme with the purpose of providing farmers with market-demanded and improved varieties, adapted to local growing conditions. The GDI programme that covers the area 'from gene to plant', is responsible for the collection, characterization, improvement, processing and storage of rice germplasms. It aims to enhance genetic diversity and develop improved rice varieties that are tolerant to both abiotic and biotic stresses, with quality consumer preference attributes, using marker-assisted selection (MAS) and GS, double haploid breeding and conventional breeding. More information on this programme can be accessed at https://www.africarice.org/genetic-diversity-and-improvement. The discovery of QTLs/genes, development of markers, and their utilization in breeding are important steps in the development of drought tolerant rice varieties.

QTL/gene discovery, marker development and application in breeding for drought tolerant varieties

The turnover rate of rice varieties remains relatively low and old drought susceptible varieties still dominate in West Africa. QTL mapping is the first procedure in the development of new varieties using modern breeding tools. We describe here a simple protocol for QTL/gene discovery under drought stress with a focus on high-throughput phenotyping and genotyping technologies.

QTL mapping involves the development of mapping populations, identification of polymorphic markers, use of polymorphic markers to genotype the mapping populations, genetic map construction, accurate phenotyping using conventional visual phenotyping or high-throughput phenotyping technologies based on drought tolerant-related traits, and identification of QTLs by integrating the genotypic and phenotypic data (Sahebi et al, 2018).

Choice of donors, recipients, and segregating populations

Donors

The development of rice varieties with improved yield in drought prone environments using conventional breeding methods is laborious and time-consuming because of the difficulty in screening for drought tolerance. To overcome this limitation, various techniques are being employed, amongst which marker-assisted breeding through the use of QTLs with large effects on drought resistance is a promising approach (Serraj et al, 2011). Progress in mapping experiments or breeding programmes for drought tolerance will result from the identification of drought tolerant donors through the screening of a large pool of germplasm.

Drought tolerant donors could be improved varieties, landraces, or wild species that have outstanding high adaptation abilities to drought or traits that can contribute to enhanced rice yield. Drought sensitivity which is one of these traits is measured by leaf rolling and leaf drying at the vegetative stage, spikelet fertility, and plant recovery from drought during the reproductive stage (IRRI, 2002). Grain yield is considered as a direct selection criterion for identification of drought tolerant donors of rice in many breeding programmes (Sandhu and Kumar, 2017). The appropriate methods for direct selection of drought tolerant lines based on grain yield include the screening of rice donor lines for grain yield under drought conditions, assessment of the performance of the donor lines under both drought stress and non-stress conditions, and then the use of appropriate statistical tools to separate the drought-tolerant lines from the susceptible ones (Sandhu and Kumar, 2017). Anyaoha et al (2018) evaluated 77 upland rice genotypes from various genetic backgrounds including local Odafa rice cultivars of south-western Nigeria, NERICA lines, landraces and other improved varieties under drought in a field condition, and found that IR68704-145-1-1-B and IR63380-16 are the best based on the selection index. Ndjiondjop et al (2010) assessed 79 *O. glaberrima* accessions for their tolerance to drought and found that RAM122, RAM100 and RAM116 have grain yield advantages of 6.7%, 16% and 40%, respectively over the best check Moroberekan from Côte d'Ivoire. More characterisation works on the African rice (*O. glaberrima*) from Sub-Sahara African countries for the identification of drought tolerant donors have been done across West Africa (Maji et al, 2011; Bocco et al, 2012; Ndjiondjop et al, 2012; Afiukwa et al, 2016; Shaibu et al, 2018).

Several drought tolerant donors have been identified, among which the most widely used in West Africa are WAB638-1, *O. glaberrima* and its wild relatives. WAB638-1, mainly used in Nigeria, is an *indica* ecotype, which is mildly tolerant to drought and adapts to Nigeria's upland and lowland ecologies (Adeboye et al, 2021). *O. glaberrima*, indigenous Africa rice, was identified by African Rice Center. It is characterized by thin leaves, small diameter and early stomata closure to prevent water loss and optimise water use efficiency (Bimpong et al, 2011), semi-upland and relatively low yield but resistant to stress (Nair, 2019). *O. glaberrima* and its associated wild types are present in almost all the West Africa germplasms. For instance, *O. glaberrima* is still being cultivated in the hills of Togo and Ghana for its robustness and the ability to perform in various ecologies and societal settings (Teeken, 2015). *O. glaberrima* still occupies an important share of cultivated rice areas in Africa, and plays an outstanding role in rice improvement programmes as it constitutes a reservoir of resistance genes to a range of biotic and abiotic stresses (Manful and Graham-Acquaah, 2016). The availability of wild relatives of the African rice such as *O. longistaminata*, *O. barthii* and *O. breviligulata* in West Africa offers opportunities beyond the pool of domestic genes of *O. sativa* and *O. glaberrima* to adapt to the increasing abiotic stress that comes with the changing climate (Nair, 2019).

Recipient parents and drought tolerant varieties

Several recipient parents such as PRIMAVERA, FUNAABOR-2 and Jasmine 85 have been used in breeding for drought tolerant varieties in West Africa. PRIMAVERA is a high-yielding *japonica* upland ecotype but it is susceptible to drought when grown in Nigeria (Adeboye et al, 2021). FUNAABOR-2 is an Odafa upland rice variety widely grown across Nigeria's western states with long grain and good nutrient characteristics (Anyaoha et al, 2018, 2019). Jasmine 85 is a popular rice variety widely grown across West Africa, which was developed from a cross between IR262/Khao Dawk Mali 105 by the International Rice Research Institute (IRRI) as IR841 and released in USA as Jasmine 85 (Bollich, 1989). Jasmine 85 was also commercially released in Ghana in 2009 (Asante, 2013) and Togo in 2022. This variety is widely grown in Benin, Ghana and Togo because of its high-yielding and grain quality attributes. Jasmine 85 was used to develop CRI-ENAPA, a Ghanaian variety which is tolerant to drought.

Several drought tolerant varieties have been released in West Africa/Africa such as CRI-ENAPA, FARO varieties (FARO65, FARO64, FARO62 and

FARO44), and NERICA varieties (NERICA8, NERICA4 and NERICA1). These drought tolerant varieties are capable of withstanding dry spells of 10 to 21 days under upland or lowland conditions, and are tolerant to meteorological and agricultural droughts. CRI-ENAPA combines the yield potential and grain quality attributes of Jasmine 85 and the drought tolerant ability of SIKAMO. AfricaRice has helped to release the drought tolerant varieties FARO65 (6.4 t/hm^2), FARO64 (5.2 t/hm^2), and FARO62 (4.0 t/hm^2) in Nigeria between 2011 and 2015. These varieties are high-yielding, adapted to upland ecologies and have early to medium maturity periods (Afiukwa et al, 2016). These varieties are mainly grown in Nigeria. NERICA varieties were developed through interspecific cross of *O. glaberrima* (African rice) and *O. sativa* (Asian rice) through *in vitro* embryo rescue and anther culture. NERICA varieties show improved tolerance to drought and resistance to pest than *O. sativa*, while these varieties record high yielding and early maturity compared to *O. glaberrima* (AfricaRice, 2008; Sonnino, 2009). NERICA varieties have been released in 30 countries in Africa (Sonnino, 2009) and their adoption has significant positive impacts on rice yield in West Africa with higher impacts in Benin and Gambia. AfricaRice released a new set of varieties with high yielding, good grain quality and tolerance to biotic and abiotic stresses in 2013, which are called Advanced Rice Varieties for Africa (ARICA) varieties. Eighteen ARICA varieties have been released in more than 11 countries in Africa including Benin, Mali, Burkina Faso, Senegal, Côte d'Ivoire, Ghana, The Gambia, Guinea, Nigeria, Togo and Uganda (https://www.africarice.org/arica). However, most of the released ARICA and NERICA varieties still need improvement to adapt with the current trend of climate change.

Phenotyping and genotyping for model drought QTL identification

The characteristic attributes of model drought tolerant rice suited for drought prone environments are varieties with high yield performance and good grain quality under drought stress and normal irrigated/rainfall conditions in multi-seasons and multi-environments, high adaptive capacity and resilience to variable biotic and abiotic stresses. Drought screening of donors and segregating populations, a crucial step in crop improvement programme, is usually conducted for upland and/or lowland rice at the reproductive stage during rainy or dry season experiments following IRRI standardised protocols for drought phenotyping screening (Sandhu and Kumar, 2017).

Approaches for discovery and introgression of grain yield and drought stress QTLs

Bi-parental QTL mapping

In many West African national crop improvement programmes, bi-parental mapping is widely used in QTL mapping approach of important agronomic and quality traits such as grain yield under drought stress. It is useful for mapping stable QTLs with large effects, but it often fails to identify QTLs with small effects. Bi-parental mapping has been used to identify QTLs for drought tolerant and grain yield-related traits with large effects in rice in West Africa (Sangodele et al, 2014; Adeboye et al, 2021). Adeboye et al (2021) mapped a total of 28 QTLs (11 major QTLs) associated with 7 agronomic characters from a cross between WAB638-1 and BRS-PRIMAVERA across two environments in Nigeria. QTLs with large effects for drought tolerance are used in MAS to improve yield of drought susceptible rice varieties. However, this kind of analysis, involving only two parents, limits the possibility of verifying QTLs in other genetic backgrounds before being applied for MAS. In order to increase genetic gain, there is a need for national breeding programmes to use GWAS and meta-analysis to identify wide genetic base and more reliable QTLs. GWAS gives room to genotyping of a large set of population with reduced or unrelated genetic backgrounds, and the use of marker-trait associations to identify genes/QTLs for complex traits such as stress tolerance based on the combined effect of all favourable alleles (Bhandari et al, 2020). GWAS has an advantage over bi-parental mapping as it takes allelic diversity and various genetic backgrounds into consideration in the entire accession collection of a breeding programme (Larkin et al, 2019). While GWAS is undoubtedly an efficient tool for plant breeding and identification of minor QTLs (Rebolledo et al, 2015), bi-parental mapping remains a valid option for the identification of major QTLs. SNPs identified through GWAS can be used as cofactors to increase the prediction accuracy of GS (Pantaliāo et al, 2016). GS is an improved version of MAS allowing an easy selection for minor QTLs and promising genotypes. It also allows the breeders to select promising single plants for field phenotype based on the genomic estimated breeding value. This makes the selection easier and the breeding cycles shorter, because multiple breeding programmes can be conducted simultaneously, and the breeding becomes cost effective (Sandhu and Kumar, 2017). Despite the breakthrough that GS brings in crop breeding, MAS is still useful for the introgression of stable major QTLs.

In addition to GS, CRISPR/Cas9 application can shorten the breeding cycle and save significant time in the development of new varieties with improved traits such as drought and salt stress compared to conventional breeding by editing targeted genome sequences (Park et al, 2022). Two extensive reviews by Romero and Gatica-Arias (2019) and Ahmad et al (2021) have thrown light on the application of CRISPR/Cas9 technology in rice breeding for stress resistance including drought and salt stresses. Lacchini et al (2020) developed CRISPR/Cas9 protocols to genetically transform African landraces. However, like GS, up-to-date limited works have been reported about the application of CRISPR/Cas9 in rice improvement in West Africa. The adoption of CRISPR/Cas9 will be an important tool for breeding for drought stress tolerance and other important agronomic traits in West Africa.

Introgression of drought tolerance QTLs

QTLs identified through bi-parental mapping, GWAS and meta-analysis are often introgressed via MAS or GS. In the last decade, breeding for drought tolerance has particularly gained the attention of African plant breeders. In Nigeria, Anyaoha et al (2019) have successfully introgressed two grain yield drought QTLs, *qDTY12.1* and *qDTY2.3* into FUNAABOR-2 through MAS coupled with phenotypic selection to improve the grain yield under drought conditions at the reproductive stage. The introgressed lines with *qDTY2.3* and *qDTY12.1* combinations manifested greater yield potential over lines with no or single QTL under drought stress and had 56.47% yield advantage over FUNAABOR-2 (the recurrent parent). In rice, the most widely used drought tolerance QTLs are *qDTY1.1* on chromosome 1, *qDTY2.2* on chromosome 2 and *qDTY12.1* on chromosome 12 (Mukherjee et al, 2018; Balija et al, 2021).

Physiology of drought tolerance

Studies on drought tolerance in rice mainly focus on agro-morphological traits; only a few works have been reported on physiological characteristics in West African countries. QTLs for relative water content (Bimpong et al, 2011; Sangodele et al, 2014; Umego et al, 2020) and chlorophyll content (Adeboye et al, 2021) have been reported. To increase genetic gain, national breeding programmes should also put emphasis on molecular function of drought-responsive genes of rice, metabolic and anti-oxidative response status in African indigenous ecotypes such as *O. glaberrima* types and other landraces. A thorough understanding of molecular and physiological dissection of these indigenous genotypes (as they contain several drought tolerant features) can help to increase genetic gain in rice productivity in West Africa.

Strategy for breeding of drought tolerant rice in West Africa

QTL profiling for important traits of core breeding germplasm is very crucial for the selection of parents for crosses. Recently, the project of enhancing institutional breeding capacity in Ghana, Senegal and Uganda to develop climate resilient crops for African smallholder farmers project and the Excellence in Breeding programme are supporting rice breeding programmes in some Sub-Saharan African countries with the genotyping of their core germplasm using SNP markers associated with known QTLs, including *qDTY1.1*, *qDTY2.2* and *qDTY12.1* for grain yield under drought stress. The use of DNA markers, high through-put phenotyping and extensive multi-locational and on-farm trials will help breeders to develop drought tolerant varieties. Participatory breeding approach involving farmers in breeding programmes should be enhanced to ensure better adoption of the improved varieties.

Even though the rapid progress in the development of molecular markers, especially SNP markers, has made genotyping easier and cost-effective, many breeding programmes in national agricultural research systems in developing countries are still finding the genotyping cost unaffordable. This could be the reason why most researchers and breeding programmes in West Africa are still largely using conventional breeding methods. Notwithstanding, some National Agricultural Research and Extension Systems and the Consultative Group on International Agricultural Research have made great strides to advance crop improvement programmes in Africa.

However, there is the need to rethink the breeding programmes in West Africa by reinforcing the capacity building of breeders, incorporating and integrating modern biotechnology and omics, biostatistics and bioinformatics tools and platforms, high-throughput phenotyping technologies and crop modelling in order to optimise and increase the genetic gains (Fig. 1). Also, strategies need to be put into place to increase the rate of dissemination and adoption of improved rice varieties by small-scale local

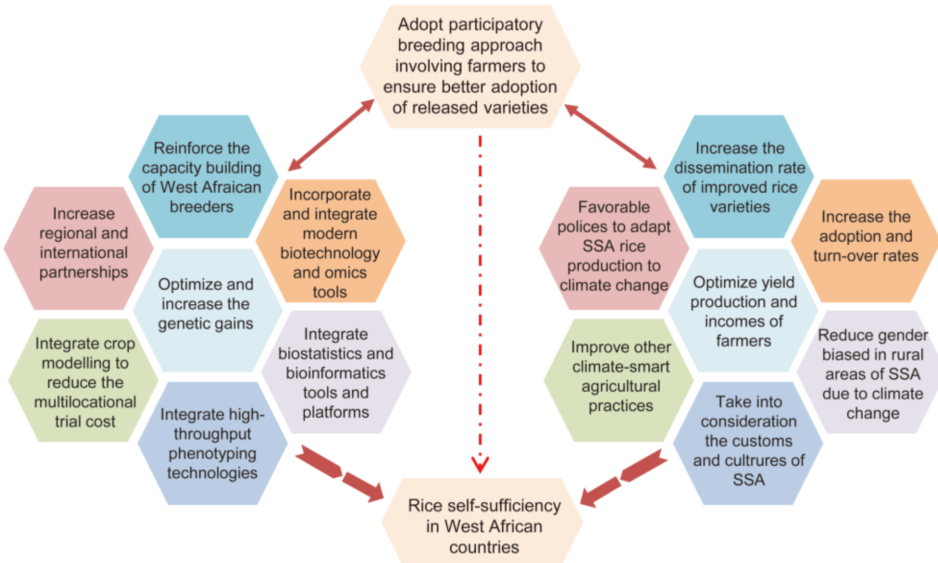

Fig. 1. Achieving rice self-sufficiency in West Africa: An integrated approach of successful breeding for drought tolerant rice in West Africa.
SSA, Sub-Saharan Africa.

rice farmers and commercial producers.

Variety development programme needs to take into account the views of women for they play a major role in variety adoption especially when it comes to improving rice varieties for their grain quality attributes and drought tolerance. Climate change is gender biased and affects more women than men, especially in rural areas of Sub-Saharan African countries (Awiti, 2022). Customs and cultures need to be taken into account in improving varieties in West African countries. Local growers and farmers mostly find it difficult to adopt a new variety if it is totally strange to them.

CONCLUSIONS

The green revolution that made Asia self-sufficient in rice production had no significant effect on Sub-Saharan Africa. In the last two decades, there have been many initiatives aimed at making Sub-Saharan Africa self-sufficient in rice production. Despite all the efforts being made to increase rice production and grain quality, there is still a deficit between consumption and production within the sub-region mainly due to increased consumption from an increasingly urbanised population. Additionally, rice production is threatened by climate change that brings about drought and flood. Under the current conditions of climate change and climate variability, the frequency of drought occurrence is expected to move from moderate to severe levels, which would endanger rice production in West Africa by increasing the risks of crop failure, yield reduction up to 100% and its year-to-year variability. There is an urgent need to develop climate-smart rice varieties suited for drought prone conditions. This can only be achieved by building strong rice research programmes through capacity building, improvement of existing technologies and introduction of new climate smart technologies, adoption of multi-disciplinary approaches to facilitate the development of rice varieties that would be tolerant not only to drought but also to other climate related stresses.

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REFERENCES

Adeboye K A, Semon M, Oyetunde O A, Oduwaye O A, Adebambo A O, Fofana M, Daniel I O. 2021. Diversity array technology (DArT)-based mapping of phenotypic variations among recombinant inbred lines of WAB638-1/PRIMAVERA under drought stress. *Euphytica*, **217**(6): 130.

Afiukwa C A, Faluyi O J, Atkinson J C, Ubi E B, Igwe O D, Akinwale O R. 2016. Screening of some rice varieties and landraces cultivated in Nigeria for drought tolerance based on phenotypic traits and their association with SSR polymorphism. *Afr J Agric Res*, **11**(29): 2599–2615.

AfricaRice (Africa Rice Center). 2008. NERICA: The new rice for Africa: A compendium. Cotonou, Benin: Africa Rice Center: 210.

Ahmad S, Tang L Q, Shahzad R, Mawia A M, Rao G S, Jamil S, Wei C, Sheng Z H, Shao G N, Wei X J, Hu P S, Mahfouz M M, Hu S K, Tang S Q. 2021. CRISPR-based crop improvements: A way forward to achieve zero hunger. *J Agric Food Chem*, **69**(30): 8307–8323.

Akpoti K, Dossou-Yovo E R, Zwart S J, Kiepe P. 2021. The potential for expansion of irrigated rice under alternate wetting and drying in Burkina Faso. *Agric Water Manag*, **247**: 106758.

Anyaoha C O, Fofana M, Gracen V E, Tongoona P B, Blay E T, Semon M, Popoola B. 2018. Yield potential of upland rice varieties under reproductive-stage drought and optimal water regimes in Nigeria. *Plant Genet Resour*, **16**(4): 378–385.

Anyaoha C O, Fofana M, Gracen V, Tongoona P, Mande S. 2019. Introgression of two drought QTLs into FUNAABOR-2 early generation backcross progenies under drought stress at reproductive stage. *Rice Sci*, **26**(1): 32–41.

Arouna A, Fatognon I A, Saito K, Futakuchi K. 2021. Moving toward rice self-sufficiency in sub-Saharan Africa by 2030: Lessons learned from 10 years of the coalition for African rice development. *World Dev Perspect*, **21**: 100291.

Asante D. 2013. Farmer and consumer preferences for rice in the Ashanti region of Ghana: Implications for rice breeding in West Africa. *J Plant Breed Crop Sci*, **5**(12): 229–238.

Awiti A O. 2022. Climate change and gender in Africa: A review of impact and gender-responsive solutions. *Front Clim*, **4**: 895950.

Balija V, Bangale U, Ponnuvel S, Barbadikar K M, Madamshetty S P, Durbha S R, Yadla H, Maganti S M. 2021. Improvement of upland rice variety by pyramiding drought tolerance QTL with two major blast resistance genes for sustainable rice production. *Rice Sci*, **28**(5): 493–500.

Bates B C, Kundzewicz Z W, Wu S, Palutikof J P. 2008. Climate Change and Water: IPCC. Technical Paper of the Intergovernmental Panel on Climate Change, IPCC Secretariat, Geneva.

Bhandari A, Sandhu N, Bartholome J, Cao-Hamadoun T V, Ahmadi N, Kumari N, Kumar A. 2020. Genome-wide association study for yield and yield related traits under reproductive stage drought in a diverse *indica-aus* rice panel. *Rice*, **13**(1): 53.

Bimpong I K, Serraj R, Chin J H, Mendoza E M T, Hernandez J, Mendioro M S. 2011. Determination of genetic variability for physiological traits related to drought tolerance in African rice (*Oryza glaberrima*). *J Plant Breed Crop Sci*, **3**(4): 60–67.

Bocco R, Lorieux M, Seck P A, Futakuchi K, Manneh B, Baimey H, Ndjiondjop M N. 2012. Agro-morphological characterization of a population of introgression lines derived from crosses between IR 64 (*Oryza sativa indica*) and TOG 5681 (*Oryza glaberrima*) for drought tolerance. *Plant Sci*, **183**: 65–76.

Bollich C N. 1989. Release of a new rice cultivar Jasmine 85 in the USA. *Int Rice Res Notes*, **14**(6): 12–14.

Caparas M, Zobel Z, Castanho A D A, Schwalm C R. 2021. Increasing risks of crop failure and water scarcity in global breadbaskets by 2030. *Environ Res Lett*, **16**(10): 104013.

Covarrubias-Pazaran G, Gebeyehu Z, Gemenet D, Werner C, Labroo M, Sirak S, Coaldrake P, Rabbi I, Kayondo S I, Parkes E, Kanju E, Mbanjo E G N, Agbona A, Kulakow P, Quinn M, Debaene J. 2022. Breeding schemes: What are they, how to formalize them, and how to improve them? *Front Plant Sci*, **12**: 791859.

Djaman K, Mel V C, Diop L, Sow A, El-Namaky R, Manneh B, Saito K, Futakuchi K, Irmak S. 2018. Effects of alternate wetting and drying irrigation regime and nitrogen fertilizer on yield and nitrogen use efficiency of irrigated rice in the Sahel. *Water*, **10**(6): 711.

FAO. 2015. The impact of natural hazards and disasters on agriculture and food security and nutrition: A call for action to build resilient livelihoods [2022-02-11]. https://www.fao.org/resilience.

FAOSTAT. 2021. FAOSTAT. Production Quantities of Rice, Paddy by Country. Food and Agriculture Organization of the United Nations (FAO), Statistics [2022-05-11]. http://www.fao.org/faostat/en/#data/QC/visualize.

Farooq M, Wahid A, Lee D J. 2009. Exogenously applied polyamines increase drought tolerance of rice by improving leaf water status, photosynthesis and membrane properties. *Acta Physiol Plant*, **31**(5): 937–945.

Foley J A, Ramankutty N, Brauman K A, Cassidy E S, Gerber J S, Johnston M, Mueller N D, O'Connell C, Ray D K, West P C, Balzer C, Bennett E M, Carpenter S R, Hill J, Monfreda C, Polasky S, Rockström J, Sheehan J, Siebert S, Tilman D, Zaks D P M. 2011. Solutions for a cultivated planet. *Nature*, **478**: 337–342.

Futakuchi K, Saito K. 2021. Integrated research for development approach to upgrade the whole rice value-chain in sub-Saharan Africa: Contribution of Africa Rice Center after NERICA (New Rice for Africa). *JARQ*, **55**: 473–481.

Haefele S M, Nelson A, Hijmans R J. 2014. Soil quality and constraints in global rice production. *Geoderma*, **235/236**: 250–259.

IRRI. 2002. Standard Evaluation System for Rice (SES). Manila, the Philippines: International Rice Research Institute.

Jarvis A, Upadhyaya H, Gowda C L L, Aggarwal P K, Fujisaka S, Anderson B. 2010. Climate Change and Its Effect on Conservation and Use of Plant Genetic Resources for Food and Agriculture and Associated Biodiversity for Food Security. Monograph: Food and Agriculture Organisation of the United Nations, UK.

Kasei R, Diekkrüger B, Leemhuis C. 2009. Drought frequency in the Volta Basin of West Africa. *Sustain Sci*, **5**(1): 89–97.

Lacchini E, Kiegle E, Castellani M, Adam H, Jouannic S, Gregis V, Kater M M. 2020. CRISPR-mediated accelerated domestication of African rice landraces. *PLoS One*, **15**(3): e0229782.

Lanceras J C, Pantuwan G, Jongdee B, Toojinda T. 2004. Quantitative trait loci associated with drought tolerance at reproductive stage in rice. *Plant Physiol*, **135**(1): 384–399.

Larkin D L, Lozada D N, Mason R E. 2019. Genomic selection: Considerations for successful implementation in wheat breeding programs. *Agronomy*, **9**(9): 479.

Lisar S Y S, Motafakkerazad R, Mossain M M, Rahm I M M. 2012. Water stress in plants: Causes, effects and responses. *In*: Rahman I M M, Hasegawa H. Water Stress. Rijeka, Croatia: InTech: 1–14.

Maji A T, Gana A S, Ukwungwu M N. 2011. Responses of *Oryza glaberrima* accessions to rice stresses and their morphological characteristics. *Afr J Agric Res*, **6**(3): 732–737.

Manful J T, Graham-Acquaah S. 2016. African Rice (*Oryza glaberrima*): A Brief History and Its Growing Importance in Current Rice Breeding Efforts. Encyclopedia of Food Grains. Amsterdam, the Netherland: Elsevier: 140–146.

Mohanty S, Wassmann R, Nelson A, Moya P, Jagadish S V K. 2013. Rice and climate change: Significance for food security and vulnerability. *In*: IRRI Discussion Paper Series No. 49. Los Banos, the Philippines: International Rice Research Institute.

Mukherjee M, Padhy B, Srinivasan B, Mahadani P, Baksh S Y, Donde R, Singh O N, Behera L, Swain P, Dash S K. 2018. Revealing genetic relationship and prospecting of novel donors among upland rice genotypes using qDTY-linked SSR markers. *Rice Sci*, 25(**6**): 308–319.

Nair K P. 2019. Utilizing crop wild relatives to combat global warming. *Adv Agron*, **153**: 175–258.

Ndjiondjop M N, Cisse F, Girma G, Sow M, Bocco R, Djedatin G, Blandine F. 2010. Morpho-agronomic and molecular characterisation of *Oryza glaberrima* germplasm from Mali. *Afr J Biotechnol*, **9**: 7409–7417.

Ndjiondjop M N, Seck P A, Lorieux M, Futakuchi K, Yao K N, Djedatin G, Sow M E, Bocco R, Cisse F, Fatondji B. 2012. Effect of drought on *Oryza glaberrima* rice accessions and *Oryza glaberrima* derived-lines. *Asian J Agric Res*, **6**(4): 144–157.

Ndjiondjop M N, Wambugu P W, Sangare J R, Gnikoua K. 2018. The effects of drought on rice cultivation in Sub-Saharan Africa and its mitigation: A review. *Afr J Agric Res*, **13**(25): 1257–1271.

Ndoye M S, Burridge J, Bhosale R, Grondin A, Laplaze L. 2022. Root traits for low input agroecosystems in Africa: Lessons from three case studies. *Plant Cell Environ*, **45**(3): 637–649.

Pantali ão G F, Narciso M, Guimar ães C, Castro A, Colombari J M, Breseghello F, Rodrigues L, Vianello R P, Borba T O, Brondani C. 2016. Genome wide association study (GWAS) for grain yield in rice cultivated under water deficit. *Genetica*, **144**(6): 651–664.

Park J R, Kim E G, Jang Y H, Jan R, Farooq M, Ubaidillah M, Kim K M. 2022. Applications of CRISPR/Cas9 as new strategies for short breeding to drought gene in rice. *Front Plant Sci*, **13**: 850441.

Prasad R, Shivay Y S, Kumar D. 2017. Current status, challenges, and opportunities in rice production. *In*: Chauhan B S, Jabran K, Mahajan G. Rice Production Worldwide. Springer International Publishing: 1–32.

Quenum G M L D, Klutse N A B, Dieng D, Laux P, Arnault J, Kodja J D, Oguntunde P G. 2019. Identification of potential drought areas in West Africa under climate change and variability. *Earth Syst Environ*, **3**(3): 429–444.

Ray D K, Gerber J S, MacDonald G K, West P C. 2015. Climate variation explains a third of global crop yield variability. *Nat Commun*, **6**: 5989.

Rebolledo M C, Dingkuhn M, Courtois B, Gibon Y, Cl ément-Vidal A, Cruz D F, Duitama J, Lorieux M, Luquet D. 2015. Phenotypic and genetic dissection of component traits for early vigour in rice using plant growth modelling, sugar content analyses and association mapping. *J Exp Bot*, **66**(18): 5555–5566.

RICOWAS. 2021. Scaling-up climate-resilient rice production in West Africa [2021-10-04]. https://www.adaptation-fund.org/wp-content/uploads/2021/05/OSS_RIE-Regional_Full_Proposal-RICOWAS_Project-Benin-al-26April2021.pdf.

Romero F M, Gatica-Arias A. 2019. CRISPR/Cas9: Development and application in rice breeding. *Rice Sci*, **26**(5): 265–281.

Sahebi M, Hanafi M M, Rafii M Y, Mahmud T M M, Azizi P, Osman M, Abiri R, Taheri S, Kalhori N, Shabanimofrad M, Miah G, Atabaki N. 2018. Improvement of drought tolerance in rice (*Oryza sativa* L.): Genetics, genomic tools, and the WRKY gene family. *Biomed Res Int*, **2018**: 3158474.

Sandhu N, Kumar A. 2017. Bridging the rice yield gaps under drought: QTLs, genes, and their use in breeding programs. *Agronomy*, **7**(2): 27.

Sangodele E A, Hanchinal R R, Hanamaratti N G, Shenoy V, Kumar V M. 2014. Analysis of drought tolerant QTL linked to physiological and productivity component traits under water-stress and non-stress in rice (*Oryza sativa* L.). *Int J Curr Res Acad Rev*, **2**(5): 108–113.

Serraj R, Kumar A, McNally K L, Slamet-Loedin I, Bruskiewich R, Mauleon R, Cairns J, Hijmans R J. 2009. Improvement of drought resistance in rice. *Adv Agron*, **103**: 41–99.

Serraj R, McNally K L, Slamet-Loedin I, Kohli A, Haefele S M, Atlin G, Kumar A. 2011. Drought resistance improvement in rice: An integrated genetic and resource management strategy. *Plant Prod Sci*, **14**(1): 1–14.

Shahryari R, Gurbanov E, Gadimov A, Hassanpanah D. 2008. Tolerance of 42 bread wheat genotypes to drought stress after anthesis. *Pak J Biol Sci*, **11**(10): 1330–1335.

Shaibu A A, Uguru M I, Sow M, Maji A T, Ndjiondjop M N, Venuprasad R. 2018. Screening African rice (*Oryza glaberrima*) for tolerance to abiotic stresses: II. Lowland drought. *Crop Sci*, **58**(1): 133–142.

Singh A, Mall A, Singh P, Verma O. 2010. Interrelationship of genetics parameters for quantitative and physiological traits in rice under irrigated and drought conditions. *Oryza*, **47**(2): 142–147.

Sonnino R. 2009. Quality food, public procurement, and sustainable development: The school meal revolution in Rome. *Environ Plan A*, **41**(2): 425–440.

Stige L C, Stave J, Chan K S, Ciannelli L, Pettorelli N, Glantz M, Herren H R, Stenseth N C. 2006. The effect of climate variation on agro-pastoral production in Africa. *Proc Natl Acad Sci USA*, **103**(9): 3049–3053.

Teeken B. 2015. African rice (*Oryza glaberrima*) cultivation in the Togo Hills: Ecological and socio-cultural cues in farmer seed selection and development. Wageningen, the Netherland: Wageningen University.

Umego C, Ntui V O, Ita E E, Opara C, Uyoh E A. 2020. Screening of rice accessions for tolerance to drought and salt stress using morphological and physiological parameters. *Am J Plant Sci*, **11**(12): 2080–2102.

van Oort P A J. 2018. Mapping abiotic stresses for rice in Africa: Drought, cold, iron toxicity, salinity and sodicity. *Field Crops Res*, **219**: 55–75.

van Oort P A J, Zwart S J. 2018. Impacts of climate change on rice production in Africa and causes of simulated yield changes. *Glob Chang Biol*, **24**(3): 1029–1045.

Wang C J, Yang W, Wang C, Gu C, Niu D D, Liu H X, Wang Y P, Guo J H. 2012. Induction of drought tolerance in cucumber plants by a consortium of three plant growth-promoting rhizobacterium strains. *PLoS One*, **7**(12): e52565.

Wassmann R, Jagadish S V K, Sumfleth K, Pathak H, Howell G, Ismail A, Serraj R, Redona E, Singh R K, Heuer S. 2009. Chapter 3 regional vulnerability of climate change impacts on Asian rice production and scope for adaptation. *Adv Agron*, **102**: 91–133.

Yadav S, Sandhu N, Singh V K, Catolos M, Kumar A. 2019. Genotyping-by-sequencing based QTL mapping for rice grain yield under reproductive stage drought stress tolerance. *Sci Rep*, **9**(1): 14326.

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