

Evolutionary Adaptations in Drought-Resilient Crops and Their Impact on Agricultural Sustainability in Nigeria

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Abstract

Drought stress poses a major threat to food production in Nigeria, especially in the northern regions where rainfall has become increasingly irregular. While modern breeding programmes continue to focus on yield improvement, they often overlook the long-term resilience needed for sustainable agriculture. This review examines how evolutionary adaptations, such as deep rooting systems, early flowering, drought-induced dormancy, stomatal regulation, and water storage mechanisms, have enabled certain crops to survive under water-limited conditions. These traits, found in indigenous crops and their wild relatives, offer untapped potential for improving drought resilience in mainstream agriculture. The study draws on data from peer-reviewed journals, agricultural reports, and research articles retrieved from Google Scholar, JSTOR, ScienceDirect, and Web of Science. Keywords like "drought adaptation," "natural selection," and "plant resilience" were used in combination with Boolean operators to refine the search. Priority was given to field-based studies with ecological and physiological relevance to Nigerian farming systems. Findings show that crops such as pearl millet, fonio, cowpea, and baobab possess adaptive traits that remain underutilised in current breeding frameworks. The review concludes that integrating these evolutionary traits into crop improvement strategies, through genomic selection and marker-assisted breeding, can support the development of varieties that are both high-yielding and drought-tolerant. It further recommends preserving the genetic diversity of indigenous crops and reorienting breeding priorities to include long-term resilience, especially in the face of Nigeria's increasing climate variability.

Keywords: Drought-Resilient Crops, Evolutionary Adaptations, Indigenous Crops, Natural Selection, Crop Breeding, Agricultural Sustainability.

Introduction

Drought stress, often mistaken for the Harmattan season in Nigeria, is one of the most critical abiotic challenges affecting agricultural production and sustainability across the country (McNicoll and Mortimore, 1989). Its growing intensity is closely linked to the shift in climate patterns, particularly the occurrence of prolonged dry spells and unpredictable

rainfall (Shiru et al., 2018). In states such as Borno, Katsina, and Sokoto, the dry season now frequently extends beyond its historical limits. This prolonged dryness negatively affects seed germination, delays seedling establishment, and leads to significant yield reductions (Eze, 2018). These challenges are compounded by ongoing desertification and the steady decrease of groundwater reserves, both of which further restrict the availability of moisture needed for healthy crop growth (O'Connor, 1995).

The severity and impact of drought are not uniform across Nigeria but vary considerably by ecological zone. The arid and semi-arid regions in the north are the most affected, experiencing longer dry periods and more intense water scarcity. However, southern regions, which were previously less vulnerable, are also beginning to show signs of climatic strain (Adenaiye, Alfred and Fasina, 2021; Ogunrinde et al., 2019). In response, farmers across different regions have adopted a range of adaptive practices to adjust to shifting weather patterns. These strategies often combine indigenous knowledge systems with locally adapted innovations aimed at preserving yields under uncertain conditions (Buhari Arin Hassan and Knight, 2023; Hillsdon, 2024).

Compared to biotic stressors, such as pest or disease outbreaks, which can be managed through pesticides or integrated biological methods, drought is a more complex and less predictable threat (Gula, 2023; Şimşek et al., 2024). While irrigation offers a possible solution, its application remains limited in most parts of Nigeria. Large-scale irrigation systems are mostly confined to commercial farms situated near major water bodies such as the Niger and Benue rivers. For the vast majority of smallholder farmers who rely on rainfall, irrigation is either inaccessible or unsustainable due to high operational costs, poor infrastructure, and increasing competition for water among agriculture, industry, and households (Takeshima and Hyacinth, 2017; You, Takeshima and Xie, 2018). As rainfall becomes less reliable and groundwater resources continue to decline, drought has emerged as a major constraint on food production and a growing threat to national food security (Ogunjimi and Adekalu, 2025). This makes the development of resilient, drought-tolerant crops not just important, but essential.

Current breeding programmes tend to focus on quick genetic fixes for drought tolerance, often overlooking adaptive traits already present in long-cultivated landraces and wild relatives (Brozynska, Furtado and Henry, 2015). These crops have developed traits like deep rooting systems, regulated stomatal conductance, and osmotic adjustment, features that enable survival under prolonged drought (Hajjar and Hodgkin, 2007; Rosero et al., 2020). Yet, their genetic value remains underutilised in mainstream crop improvement strategies (Guadarrama-Escobar et al., 2024; Dempewolf et al., 2014).

Despite growing attention to drought-resilient agriculture, few studies have systematically reviewed the evolutionary traits of indigenous and wild crop species in Nigeria and their relevance for modern breeding. This gap limits the integration of naturally evolved resilience into formal agricultural systems.

This review addresses that gap by highlighting the adaptive traits developed through natural selection in crops commonly grown across Nigeria's ecological zones. It examines

how these traits, such as deep root systems, drought-induced dormancy, and stomatal regulation, can be incorporated into breeding programmes through genomic tools and targeted selection. By doing so, the study offers a practical framework for aligning evolutionary biology with agricultural innovation, providing insights that are critical for building a climate-resilient food system in Nigeria.

Problem Statement

Although several drought resilience efforts are underway in Nigeria, current research and breeding programmes often emphasise laboratory-driven genetic improvements and imported crop models that may not reflect local ecological realities. Meanwhile, indigenous crops and their wild relatives, many of which have developed natural drought survival mechanisms over decades, remain poorly studied and underutilised in breeding pipelines. This disconnect is particularly evident in the lack of attention to long-established traits such as drought-induced dormancy, deep rooting, and stomatal regulation, which have enabled these crops to thrive in Nigeria's increasingly water-stressed environments. The broader academic literature has yet to systematically explore how these evolutionary traits can be translated into crop improvement frameworks suited for Nigeria's diverse agroecological zones. This review addresses that gap by evaluating adaptive features across selected drought-resilient species and outlining how such traits can inform sustainable, field-relevant breeding approaches in the face of ongoing climate uncertainty.

Objectives of the Review

- Examine the role of natural selection in shaping drought adaptation mechanisms in indigenous and underutilised crops within Nigeria's ecological zones.
- Identify key evolutionary traits, such as deep rooting systems, stomatal regulation, osmotic adjustment, and drought-induced dormancy, that contribute to drought resilience.
- Assess the extent to which these traits are underutilised in mainstream breeding programmes, particularly those focused on high-yield varieties.
- Evaluate the limitations of current breeding approaches that prioritise short-term yield gains over long-term resilience.
- Explore how adaptive traits can be integrated into crop improvement efforts using field-relevant breeding strategies, including genomic selection and marker-assisted breeding.
- Recommend a more balanced breeding approach that preserves yield potential while improving the ability of crops to survive under prolonged water deficit.

Drought-Resilient Crops: Harnessing Evolution for Food Security in Nigeria

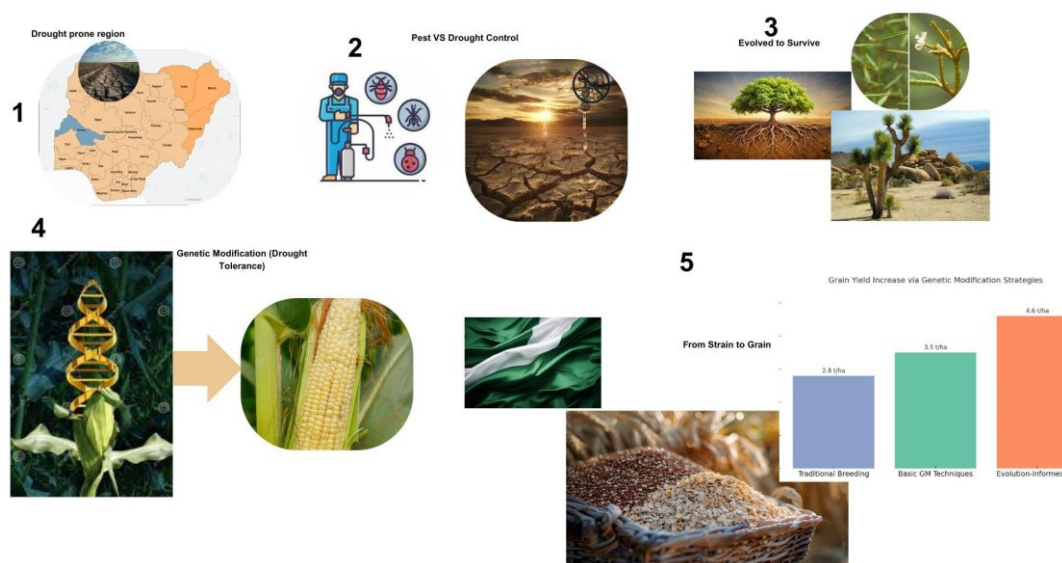


Figure 1: Conceptual overview of drought stress impact and the role of evolutionary adaptation in enhancing crop resilience in Nigeria.

Source: Graphic adapted from Canva design template (2025).

Methodology

The materials analysed in this review were obtained primarily from different peer-reviewed journals, review papers, conference proceedings, and other relevant research works that directly addressed the focus of this study all of which were from reputable and credible academic databases, including Google Scholar, Web of Science, Scopus, ScienceDirect, JSTOR, PubMed Central, SpringerLink, and BioMed Central.

The reviewed papers were either available as open-access (free to readers) or subscription-based access (available only to subscribers); this was done to ensure a comprehensive and exhaustive approach to the available information, as it concerned my search focus, an approach that provided a balanced perspective across the spectrum of current research. To narrow down the search for appropriate literature, relevant keywords and phrases were employed. These included: "plant adaptation," "natural selection," "drought stress," "adaptive traits," "drought tolerance," "evolutionary traits," "deep rooting," "stomatal regulation," "osmotic adjustment," "drought-induced dormancy," "evolutionary ecology," "plant water-use efficiency," and "climate resilience in crops". These terms were used with Boolean operators such as AND, OR, and NOT to refine the search process. AND and OR were used to get a broad list of relevant materials, while NOT was used to exclude unrelated or less useful materials. Although there was no strict restriction on publication year, more recent studies that built upon earlier findings were prioritised, especially those that offered new insights or updated perspectives.

Initially, articles were screened by their titles and abstracts to eliminate those that lacked relevance to the subject matter. Only those that engaged meaningfully with the link between natural selection and drought adaptation were retained for full-text review.

Special attention was given to empirical studies and critical reviews that addressed plant-level responses to drought from a physiological, morphological, or evolutionary perspective. Papers that focused entirely on molecular-level mechanisms without paying attention to broader ecological or adaptive context were not considered, as they fell outside the scope of this review.

Once a relevant study was identified, the data were carefully reviewed to identify common patterns across traits and adaptive strategies. Focus was placed on drought-resilience features such as efficient stomatal regulation, root system modifications, osmotic adjustment, and stress-induced dormancy. These patterns were then grouped into broad categories to highlight evolutionary trends and explore how such traits can be incorporated into breeding programs to enhance the resilience of crops, especially in the northern Nigeria region.

Even though this review does not fall under the category of a systematic meta-analysis, maximum effort was made to ensure that the process was rigorous, transparent, and methodical. The final product presents a comprehensive narrative of the role that natural selection plays in equipping plants to survive and thrive under drought stress. The lessons learned are both scientifically grounded and practically relevant to ongoing challenges in agriculture.

Table 1: Overview of Research on Crop Adaptation to Drought Stress

Author	Focus/Research Area	Methodology Summary	Key Findings	Relevance to Drought Adaptation
Adenaiye, O.G., Alfred, S.D.Y. and Fasina, O.O. (2021).	Farmers' utilisation of climate change adaptation strategies across selected agro-ecological zones in Nigeria	Survey research across different agro-ecological zones using structured questionnaires and interviews to collect data from farmers on adaptation practices	identified that farmers employ a mix of indigenous knowledge and modern techniques such as crop diversification, early planting, and the use of drought-resistant varieties to cope with climate change impacts	Demonstrates how practical, field-level adaptation strategies are essential responses to drought stress, reinforcing the need for integrating adaptive agricultural practices with scientific research
Agbicodo, E.M., Fatokun, C.A., Muranaka, S., Visser, R.G.F. and Linden van der, C.G. (2009)	Breeding cowpea (<i>Vigna unguiculata</i>) for drought tolerance: Challenges, achievements, and future directions	Review of breeding strategies, genetic studies, and recent advances. Discusses the use of molecular markers and QTL (quantitative trait loci) mapping for drought tolerance traits	Although drought tolerance-related QTLs have not been definitively identified in cowpea yet, advances in molecular breeding, understanding physiological traits, and the use of genomics tools are paving the way for future success	Highlights the genetic complexity of drought tolerance and the need for improved breeding techniques to develop cowpea varieties that can better withstand drought, essential for food security in drought-prone regions
Asadu, C. (2015)	Genetic diversity and the role of traditional landraces in crop improvement.	Conceptual and comparative analysis using examples from different crop species to demonstrate the adaptive value of landraces.	Landraces offer a reservoir of genetic traits suited to local stress conditions and can improve resilience when used in breeding.	Supports the conservation and genetic use of local crop varieties in breeding for drought tolerance and climate-smart agriculture.
Bapela, T., Shimelis, H., Tsilo, T.J. and Mathew, I. (2022)	Challenges and opportunities in Nigeria's agricultural sector.	Descriptive policy analysis supported by empirical data on agricultural productivity and inputs.	Identifies structural weaknesses in the Nigerian agricultural system, such as low mechanisation, poor soil fertility, and limited adaptation.	Points to systemic challenges that must be addressed before adaptation strategies (like drought-tolerant crops) can be effectively implemented.
Bassi, J. and Dugje, I. (2020)	Breeding strategies and genomic technologies for drought-tolerant wheat.	An extensive literature review of conventional and molecular breeding techniques for wheat drought resilience.	Breeding for drought tolerance has progressed through QTL mapping, marker-assisted selection, and transgenic approaches, though challenges remain.	Demonstrates the critical role of advanced plant breeding in producing wheat cultivars suited for water-scarce environments.
Basu, S., Ramegowda, V., Kumar, A. and Pereira, A. (2016)	Yield outcomes in cowpea-millet intercropping systems in dryland Nigeria.	Field trial in Maiduguri assessing yield performance across different planting times and varieties.	The early introduction of cowpea increases overall productivity and supports better resource use in intercropping.	Illustrates practical on-field solutions like intercropping and timing adjustments to cope with erratic rainfall patterns.
Brozynska, M., Furtado, A. and Henry, R.J. (2015).	Genomic technologies applied to wild crop relatives for improving stress tolerance.	Review of sequencing methods and gene identification from wild species to enhance breeding strategies.	Wild relatives hold untapped genetic resources that can be harnessed through genomics to address abiotic stresses.	Highlights the importance of broadening genetic diversity to boost crop drought resilience.
Buhari Arin Hassan and Knight, J. (2023)	Adaptation strategies among Nigerian smallholder farmers facing climate variability.	Field surveys and household interviews with quantitative and qualitative analysis of adaptive behaviours.	Farmers adapt via practices such as changing planting dates, adopting drought-tolerant crops, and using traditional knowledge.	Validates community-led adaptation as a vital component of climate resilience in agriculture.
Cattivelli, L., et al. (2008).	Multidisciplinary strategies for developing drought-tolerant crops.	Integrative literature review of physiology, molecular biology, and genetic breeding methods.	Emphasises coordinated approaches combining phenotyping, genomics, and breeding for enhanced drought tolerance.	Encourages systemic frameworks that link molecular research with field-level crop improvement.
Deafalla, T.H.H. (2022)	The potential of Baobab (<i>Adansonia digitata</i>) in adapting to environmental change.	Examination of Baobab's potential for adaptation to climate change, with a focus on its drought tolerance.	Baobab is highly resilient to drought and environmental changes, making it a promising crop for arid regions.	The study highlights Baobab as an example of a drought-tolerant plant with potential for adaptation to changing climates.

Degu, H., Ohta, M. and Fujimura, T. (2008)	Physiological adaptations of tef under drought stress.	Controlled experiments measuring root development and plant response under water deficit.	Tef demonstrates deep rooting and delayed stomatal closure, aiding survival in dry conditions.	Identifies traits relevant for breeding tef and other cereals for water-limited environments.
Dempewolf, H., et al. (2014)	Global conservation and use of crop wild relatives (CWRs).	International project integrating collection, genebanking, and breeding applications of CWRs.	Underscores the urgency of conserving CWRs for climate-resilient breeding.	Positions CWRs as strategic assets for drought adaptation through genetic enhancement.
De Smedt, S., et al. (2012)	Drought tolerance variability in Baobab seedlings across African regions.	Experimental drought treatments on seedlings from different ecotypes, measuring physiological responses.	West African ecotypes showed higher drought tolerance than southeastern types, reflecting local adaptation.	Demonstrates intraspecific variation that can inform domestication and breeding of underutilised crops.
Devi, E.L., et al. (2017)	Use of molecular markers in breeding stress-resilient varieties.	Review of MAS approaches, QTL mapping, and marker validation across multiple crops.	MAS expedites the breeding process by precisely transferring drought-resistance traits.	Advocates for marker-based breeding as a reliable tool to scale drought-resilient agriculture.
Doležal, J., et al. (2021).	Plant anatomical changes in waterlogged and aquatic environments.	Comparative anatomical analysis using phylogenetic and ecological data across diverse species.	Aquatic plants develop specific structural traits such as aerenchyma and reduced xylem.	While focused on flooding, the study offers insights into structural plasticity, which can be analogously explored in drought-tolerant species.
Endang, N., et al. (2024)	Screening drought-resistant cassava varieties using PEG-induced water stress.	Lab-based simulation of drought using PEG 6000 to assess physiological and morphological responses in cassava genotypes.	Identified cassava accessions with high resistance under osmotic stress, suggesting potential for drought-prone regions.	Supports low-cost screening of drought-tolerant varieties for climate-resilient agriculture.
Eze, J.N. (2018)	Socioeconomic effects of drought on Nigerian households.	Field survey-based analysis of livelihood impacts, coping mechanisms, and vulnerability.	Frequent droughts have led to food insecurity and migration; local adaptive capacities are overstretched.	Highlights the real-life consequences of drought and the urgent need for both agricultural and social interventions.
Feedipedia (n.d.)	Agronomic and nutritional profile of fonio.	Descriptive review of the plant's adaptability, resilience, and feed value.	Fonio thrives in poor soils and drought-prone regions, offering resilience and early maturity.	A neglected crop with great potential for dryland agriculture and food diversification.
George, T.T., Obilana, A.O. and Oyeyinka, S.A. (2020)	Revival and promotion of underutilised African legume.	Literature review and historical assessment of its cultivation and nutritional value.	The crop is nutrient-rich and drought-resilient but under-researched and underfunded.	Promoting neglected crops like AYB can enhance agricultural sustainability in drylands.
Guadarrama-Escobar, O., et al. (2024)	Reevaluating traditional knowledge and genetic potential for drought adaptation.	Discussion of integrating ancient landraces and indigenous knowledge with modern science.	Traditional varieties often hold forgotten adaptive traits that are vital in modern breeding.	Calls for revalorisation of traditional practices and local germplasm for climate-smart farming.
Gula, L.T. (2023)	Ongoing research initiatives on pest management and crop protection.	Narrative blog highlighting research at the intersection of crop resistance and pest threats.	Research is advancing biocontrol and integrated pest management methods, especially under climate stress.	Stressed crops are more susceptible to pests; integrated management supports resilience in drought-hit farms.
Hajjar, R. and Hodgkin, T. (2007)	Trends and outcomes of using crop wild relatives in breeding.	Meta-analysis of breeding programmes globally utilising wild relatives.	Wild relatives have contributed to disease resistance, drought tolerance, and abiotic stress resilience.	Supports the case for mainstreaming wild relatives in climate-resilient crop development.
Hillsdon, M. (2024)	Controversies surrounding agricultural intensification in Africa.	Investigative report capturing policy debates, farmer responses, and ecological concerns.	While some argue for high-tech intensification, critics raise concerns about biodiversity loss and sustainability.	Stresses need for balance between productivity and ecological resilience in drought-prone contexts.
Ilkay, Y., et al. (2023)	Physiological adaptations to drought at the leaf level.	Review of morphological responses such as stomatal	Leaves adapt via structural changes that reduce water loss and improve efficiency under drought.	Leaf traits offer measurable indicators for selecting drought-tolerant cultivars.

		density, cuticle thickness, and leaf rolling.		
Joshi, R.K., Bharat, S.S. and Mishra, R. (2020)	Genome editing for abiotic stress resilience.	Review of CRISPR applications in improving plant response to drought.	CRISPR offers precision and speed in editing drought-response genes with minimal off-target effects.	Offers futuristic tools for targeted breeding of climate-resilient crops.
Kooyers, N.J. (2015)	Natural selection patterns in herbaceous species under drought.	Comparative ecological and evolutionary analysis of life history strategies.	Species develop drought escape (early flowering) or avoidance (deep roots, water conservation) based on habitat.	Reveals how adaptive strategies can inform breeding targets for different environments.
McNicoll, G. and Mortimore, M. (1989)	Historical and policy insights on drought adaptation in West Africa.	Case-based socio-ecological analysis of farmer practices and institutional responses.	Farmers have long developed coping strategies, but policy interventions are often misaligned or under resourced.	Highlights the importance of integrating indigenous knowledge and grassroots innovation with formal policy.
Ndlovu, E., van Staden, J., and Maphosa, M. (2021)	Impact of heat and moisture stress on sorghum's growth and physiological responses.	Experimental analysis of sorghum under varying stress conditions, focusing on its acclimation mechanisms.	Sorghum exhibits significant changes in growth patterns and physiological processes under combined heat and moisture stress. Key adaptations include enhanced water retention and metabolic adjustments.	Provides insight into crop resilience mechanisms, highlighting the potential for improving drought tolerance in sorghum through selective breeding.
Naija Scholar (2024a)	Opportunities for funding plant breeding research in Nigeria.	Review of available funding sources for plant breeding research, including government and private sector initiatives.	Funding for plant breeding research in Nigeria is growing, but remains highly dependent on both government policies and international donors.	This study underlines the importance of financial investment in agricultural research, which is critical for developing drought-resistant crops.
Naija Scholar (2024b)	Future directions for plant breeding and seed science in Nigeria.	Discussion of trends and challenges in plant breeding in Nigeria, with a focus on sustainable practices and technological innovation.	The future of plant breeding in Nigeria hinges on the integration of advanced genomics and sustainable practices, as well as stronger policy frameworks.	Focuses on the role of plant breeding in improving drought resilience, particularly through the development of climate-resilient varieties.
Oagile, O. (2005)	Morphological and genetic properties of the African yam bean, with an emphasis on nitrogen fixation.	Study of the morphology, clonal propagation techniques, and nitrogen-fixing capacity of the African yam bean.	The African yam bean is a promising crop for improving soil fertility and supporting sustainable agriculture in arid regions.	Highlights the African yam bean's potential in water-scarce environments due to its drought tolerance and nitrogen-fixing ability, contributing to soil health.
O'Connor, T.G. (1995)	Impact of drought and grazing on savanna grassland ecosystems.	Field study investigating the interaction between drought and grazing pressure on vegetation in savanna ecosystems.	Drought significantly transforms grassland composition, with grazing exacerbating the degradation, making ecosystems more vulnerable.	Shows the compounded effects of drought and human activity (grazing), underscoring the importance of integrated land management for drought resilience.
Ogunjimi, L.A.O. and Adekalu, K.O. (2025)	Challenges faced by small-scale irrigation systems in Nigeria, with a focus on Fadama.	Analysis of the operational challenges and constraints of small-scale irrigation schemes, with a focus on policy, resources, and technology.	Small-scale irrigation in Nigeria faces significant issues, including poor infrastructure, limited access to financing, and inadequate water management.	Addresses the critical role of improving irrigation systems in mitigating the impacts of drought on agriculture, especially in arid regions.
Ogunrinde, A.T., Oguntunde, P.G., Akinwumiju, A.S., and Fasinmirin, J.T. (2019)	Analysis of changes in rainfall patterns and drought indices in Nigeria over 34 years.	Statistical analysis of rainfall data and drought indices to assess trends in drought frequency and intensity in Nigeria.	There has been a noticeable increase in drought intensity and frequency in Nigeria, particularly in the northern regions.	This study highlights the need for adaptive strategies in agriculture, such as drought-resistant crop varieties and better water management practices.
Orek, C. (2025)	Evaluation of cassava genotypes for drought tolerance.	Field trials assessing cassava varieties for drought resilience and physiological performance under water deficit conditions.	Certain cassava genotypes show strong resistance to drought, with higher yields and better physiological traits under water deficit conditions.	Cassava is a staple crop in many drought-prone areas, and this study contributes to identifying drought-tolerant varieties for enhanced food security.

Padilla, F.M. and Pugnaire, F.I. (2007)	Survival of Mediterranean woody plants during drought conditions, with a focus on rooting depth.	Field experiments to assess how root depth influences drought survival in Mediterranean woody seedlings.	Root depth is a critical factor in determining seedling survival during drought, with deeper roots improving water access and resilience.	Understanding the role of root depth in drought tolerance is essential for improving the survival of drought-sensitive plant species.
Pavli, O.I., Vlachos, C.E., Kalloniati, C., Flemetakis, E., and Skaracis, G.N. (2013)	Effect of drought on sorghum metabolism.	Metabolite profiling of sorghum under drought stress to identify metabolic changes linked to drought resilience.	Drought significantly alters the metabolism of sorghum, affecting its growth and yield, but certain metabolic pathways may aid in drought resistance.	Understanding metabolic changes in crops like sorghum can help in breeding more drought-tolerant varieties.
Ramírez-Valiente, J.A., et al. (2018)	Genetic divergence in leaf traits across a precipitation gradient in tropical oaks.	Study of genetic variations in tropical oak species in response to varying precipitation levels, focusing on leaf traits.	Natural selection plays a crucial role in the genetic divergence of leaf traits, influencing drought resistance in tropical oak species.	Understanding genetic divergence in drought-resistant plants is essential for enhancing the resilience of forestry systems to changing rainfall patterns.
Rauf, S., Al-Khayri, J.M., M. Zaharieva, Philippe Monneveux, and Khalil, F. (2016)	Breeding strategies to improve drought tolerance in crops.	Review of various breeding strategies aimed at improving drought resistance in staple crops.	Several breeding strategies, including genetic modification and conventional breeding, can significantly enhance drought tolerance in crops.	Breeding drought-tolerant crops is one of the most direct ways to combat the effects of drought and improve food security.
Romheld, V. (1987)	Strategies for iron acquisition in higher plants.	Examination of different mechanisms by which plants acquire iron, with a focus on drought conditions.	Plants employ various strategies to acquire iron, and these can be influenced by environmental factors, including drought.	Understanding iron acquisition in plants is crucial for enhancing their drought tolerance.
Rosero, A., Granda, L., Berdugo-Cely, J.A., Šamajová, O., Šamaj, J., and Cerkal, R. (2020)	Breeding for drought tolerance and incorporating underutilised crops into production systems.	Research on dual strategies for improving drought tolerance and enhancing resilience in agricultural systems through underutilised crops.	Integrating underutilised crops into mainstream agricultural systems can boost resilience to water scarcity.	The study highlights sustainable approaches to improve drought resilience in crops and farming systems.
Salgotra, R.K., and Chauhan, B.S. (2023)	Genetic diversity, conservation, and utilisation of plant genetic resources.	Review of genetic diversity in plants and strategies for their conservation and use in breeding programs.	Genetic diversity is vital for improving drought tolerance in crops, and its conservation is key to sustainable agriculture.	The study emphasises the need to conserve genetic resources to aid drought adaptation.
Sarma, H.H., Borah, S.K., Dutta, N., Sultana, N., Nath, H., and Das, B.C. (2024)	Innovative approaches for climate-resilient farming.	Exploration of strategies to mitigate the effects of environmental shifts and climate change on farming systems.	Innovative farming techniques, including climate-resilient crops and water-saving technologies, are key to adapting to climate change.	The study focuses on strategies that enhance the ability of farming systems to withstand droughts.
Seleiman, M.F., et al. (2021)	Drought stress impacts plants and approaches to mitigate its effects.	Review of different strategies to alleviate the adverse effects of drought stress on plants.	Various agronomic and biotechnological strategies can help mitigate drought stress in plants.	Provides insight into practical approaches for improving plant resilience to drought.
Shiru, M., Shahid, S., Alias, N., and Chung, E.-S. (2018)	Trend analysis of droughts during crop-growing seasons in Nigeria.	Analysis of historical drought trends in Nigeria and their impact on agricultural production.	Droughts have been increasing in frequency and severity, severely impacting agricultural yields in Nigeria.	Understanding drought patterns in Nigeria is critical for developing effective adaptation strategies.
Shoaib, M., Banerjee, B.P., Hayden, M., and Kant, S. (2022)	Roots' drought adaptive traits in crop improvement.	Investigation into the role of root traits in enhancing crop tolerance to drought stress.	Roots with enhanced drought-adaptive traits can significantly improve crop resilience under water-deficient conditions.	Improving root traits is a promising avenue for breeding drought-resistant crops.
Shrestha, N., Hu, H., Shrestha, K., and Doust, A.N. (2023)	Pearl millet's response to drought.	Review of pearl millet's physiological response to drought stress, focusing on its drought tolerance mechanisms.	Pearl millet exhibits significant drought tolerance, making it a valuable crop for arid regions.	The review highlights the potential of pearl millet as a resilient crop for drought-prone areas.
Şimşek, Ö., Isak, M.A., Dönmez, D., Dalda Şekerçi, A.,	Biotechnological interventions to mitigate drought stress in plants.	Biotechnological interventions to mitigate drought stress in plants.	Biotechnological interventions can significantly improve plants' ability to withstand drought stress.	Provides insight into the potential of biotechnology to enhance drought resilience in agriculture.

Izgü, T., and Kaçar, Y.A. (2024)				
Takeshima, H., and Hyacinth, E. (2017)	Constraints for small-scale private irrigation systems in the North Central Zone of Nigeria.	Analysis of the challenges faced by small-scale irrigation systems and their impact on agricultural productivity.	Small-scale irrigation systems face significant challenges, including poor infrastructure and a lack of support, which hinder their effectiveness.	Improving small-scale irrigation systems can significantly enhance drought resilience for farmers in Nigeria.
Tandzi, N.L., and Mutengwa, S.C. (2020)	Factors affecting crop yield, with a focus on climate change and food security.	Examination of various factors that influence crop yield, particularly in the context of climate change.	Climate change significantly affects crop yields, and understanding these factors is key to improving food security.	The study provides insight into how environmental factors, including drought, can affect crop productivity and the need for adaptive strategies.
Tankari, M., et al. (2021)	Drought priming in cowpea and its effects on water status, photosynthesis, and water productivity.	Research on drought priming techniques and their effects on cowpea under post-anthesis drought stress conditions.	Drought priming improves water use efficiency and photosynthesis, enhancing water productivity in cowpea.	The study demonstrates how priming can improve drought resilience in crops, contributing to more efficient water use.
Theophilus, D., and Jain, T. (2024)	Ecological, cultural, and morphological analysis of <i>Adansonia digitata</i> L. (Baobab) in Karnataka, India.	An analysis of the ecological, cultural, and morphological features of Baobab trees in a specific region of India.	Baobab trees are highly adaptable and important in the cultural and ecological context, with resilience to harsh environmental conditions.	Baobab is a drought-tolerant species, and this study emphasises its potential for climate resilience in dry regions.
Vadez, V., Hash, T., Bidinger, F.R., and Kholova, J. (2012)	Phenotyping pearl millet for drought adaptation.	Research on the phenotypic traits of pearl millet that contribute to its drought tolerance.	Pearl millet exhibits various phenotypic traits that enhance its ability to survive and thrive under drought conditions.	The study focuses on pearl millet as a model crop for breeding drought-resistant varieties.
Yoselin, B., et al. (2023)	Enhancing climate change resilience in crops.	A review of strategies to enhance crop resilience to climate change, focusing on drought tolerance and other stress factors.	Improving genetic traits, water management, and farming practices can help crops adapt to climate change.	The study provides key insights into enhancing drought resilience in crops through various strategies.
You, L., Takeshima, H., and Xie, H. (2018)	Growth in Nigerian agriculture through small-scale irrigation.	Examination of the potential for small-scale irrigation to boost agricultural productivity in Nigeria.	Small-scale irrigation can significantly enhance crop yields and water use efficiency, helping farmers cope with drought.	Improving irrigation systems is a critical strategy for adapting to water scarcity and drought conditions in Nigeria.
Zahedi, S.M., Karimi, M., Venditti, A., Zahra, N., Siddique, K.H.M., and Farooq, M. (2024)	The role of anatomical and morphological characteristics in plant adaptation to drought.	Analysis of how anatomical and morphological traits of plants contribute to their ability to maintain water status under drought stress.	Certain plant characteristics, such as leaf structure and root depth, are crucial for maintaining water status during drought.	Understanding these traits can guide breeding programs aimed at improving drought resilience in crops.

Discussions

Evolutionary Mechanisms of Drought Adaptation

Drought stress triggers the evolution of adaptive traits in plants situated in water-limited regions. This evolution is not spontaneous but an occurrence that takes generations to establish (Zahedi et al., 2024). These traits evolve as a survival strategy that is triggered by prolonged drought stress, they make it possible for the affected plant to persist, reproduce and reduce the extinction of valuable food crops (Cattivelli et al., 2008). Natural selection in these regions has consistently favoured the evolution of traits that enhance plant survival under drought conditions (Bapela et al., 2022), unlike the modern breeding programs that primarily focus on increasing yield and neglecting long-term resilience. Natural selection ensures the continuity of these traits. To develop crops that can withstand Nigeria's unpredictable weather conditions, we must incorporate the ideas gained from studying these naturally evolved traits and integrate them into breeding programs in such a way that productivity and yield efficiency are retained (Rauf et al., 2016).

Role of Natural Selection in Ensuring Plant Adaptation to Drought Stress

Natural selection is one of the main factors that will continuously ensure the sustainability and survival of plants in arid and semi-arid regions, as it determines the genetic composition of plants in this region, hence ensuring that only the resilient varieties are bred and interbred (Ramírez-Valiente et al., 2018). It ensures that those species that have evolved physiological and morphological traits needed to survive water stress become predominant while less-adapted variants become extinct and decline over successive generations (Basu et al., 2016). This evolutionary process has resulted in a plant community with traits that have diverse drought-resilient phenotypes and specialised mechanisms for surviving water stress (Kooyers, 2015).

Sorghum (*Sorghum bicolor*) is an example of plants that undergo metabolic dormancy to adapt to drought stress (Pavli et al., 2013). During prolonged drought strain, sorghum reduces metabolic activity to conserve energy and minimise water loss. Once water becomes available, it resumes growth and development (Ndlovu, van Staden and Maphosa, 2021). This allows them to survive in water-deficient regions while other cereals suffer or die from this stress (Pavli et al., 2013).

In contrast, species such as pearl millet (*Pennisetum glaucum*) and cowpea (*Vigna unguiculata*) exhibit drought escape mechanisms by completing their life cycle within a short period, thereby avoiding prolonged exposure to drought stress (Agbicodo et al., 2009; Shrestha et al., 2023). These crops synchronise their flowering and seed production with the brief periods of soil moisture available to them, which follow seasonal rainfall (Bassi and Dugje, 2020). This adaptation mechanism allows them to finish their reproductive cycle before moisture depletion becomes critical, thus reducing their exposure to prolonged drought stress and improving their chances of survival and continuity despite this stress (Agbicodo et al., 2009; Shrestha et al., 2023).

These naturally selected traits offer valuable insights needed for enhancing crop resilience in Nigeria (Basu et al., 2016). Incorporating the genetic resources gained from drought-adapted species into breeding programs could facilitate the development of cultivars that sustain productivity under unpredictable climatic variability (Yoselin et al., 2023). This approach has the potential to strengthen agricultural sustainability and improve food security in the long term (Romheld, 1987).

Major Evolutionary Adaptations to Drought Stress

Morphological Adaptations

Plants, when subjected to stress, evolve distinct morphological traits that enhance their resilience and survival. These adaptations enable them to either maximise water uptake, reduce water loss, or escape prolonged drought stress by timely adjusting their life cycles.

Root System Plasticity

The root architecture of a plant plays a crucial role in enhancing its adaptation to drought stress, especially as it relates to Nigeria's semi-arid and savanna regions, where severe drought stress is experienced due to irregular rainfall and the presence of sandy soils. To survive in this region, most indigenous drought-resilient crops have evolved deep taproots and lateral roots, which spread out in the soil to be able to obtain water from deeper soil layers (Padilla and Pugnaire, 2007).

- African yam bean (*Sphenostylis stenocarpa*) develops a strong taproot that goes deep into the soil, which helps it to source for water even when the rains are delayed for long periods. This makes it suitable for rain-fed farming systems, especially in places where rainfall is not always reliable (George, Obilana and Oyeyinka, 2020; Oagile, 2005).
- Pearl millet (*Pennisetum glaucum*), a common crop in northern Nigeria, has a flexible root system. It has taproots that grow deep into the ground to be able to have access to water stored in lower layers of the soil, and it also spreads its lateral roots near the surface to take advantage of any quick rainfall (Vadez et al., 2012). This gives it a better chance of surviving drought stress and a better chance of producing yield during this stress.

These root adaptations are important for developing crop varieties that can withstand drought and still produce good yields, especially as Nigeria's climate continues to change (Shoaib et al., 2022).

Leaf Modifications

Leaf morphology plays a critical role in minimising water loss and helps to improve drought tolerance. Several Nigerian crops have evolved protective leaf modifications, such as waxy cuticles, reduced leaf area, and trichomes, to limit transpiration (Ilkay et al., 2023).

- Cassava (*Manihot esculenta*) forms a thick waxy cuticle over its leaves, which reduces water loss, particularly as it relates to the hot, dry weather conditions of the northern and middle belt region of Nigeria. This adaptation allows cassava to survive prolonged drought stress and also enables it to maintain productivity (Orek, 2025).
- Cowpea (*Vigna unguiculata*), another key drought-resilient crop, produces leaf hairs (trichomes) that lower leaf temperature and create a boundary layer that slows down transpiration (Tankari et al., 2021). This microstructural adaptation is essential in semi-arid farming systems where water scarcity is recurrent.
- Some drought-adapted crops, such as fonio (*Digitaria exilis*), reduce leaf surface area by forming narrower leaves, which decreases direct exposure to sunlight and limits water loss through transpiration. This allows fonio to thrive in low-rainfall regions (Bassi and Dugje, 2020).

These adaptations ensure that Nigerian staple crops continue to produce food under unpredictable drought conditions, making them valuable genetic resources for future breeding programmes.

Drought Escape Mechanisms

Unlike deep-rooted crops that withstand drought, some plants escape it altogether by completing their life cycle rapidly, they take advantage of short rainy seasons before drought sets in. This is particularly critical for crops grown in northern Nigeria, where rainfall duration is limited.

- Pearl millet (*Pennisetum glaucum*) exhibits a short reproductive cycle, which allows it to flower and produce seeds before severe water deficits occur (Shrestha et al., 2023).
- Cowpea (*Vigna unguiculata*), similarly, has evolved early flowering and rapid seed development, which synchronises its growth with the limited soil moisture available after seasonal rains (Agbicodo et al., 2009).

These drought escape strategies are crucial for maintaining food security in rain-fed farming systems where water availability is highly unpredictable.

Microstructural Adaptations

In addition to large-scale morphological changes, many drought-resilient crops in Nigeria have evolved microstructural adaptations at the cellular and tissue levels to conserve moisture and optimise water use. These adaptations play a critical role in enhancing drought tolerance without compromising metabolic function.

Water Storage

Some perennial and woody species have evolved tissue that stores water for them; this enables them to survive prolonged drought stress. These plants accumulate and gradually utilise stored water to maintain their physiological processes during dry seasons. One of the most well-adapted examples is the baobab (*Adansonia digitata*), a species prominent in the savanna region of northern Nigeria. The baobab conserves water by storing substantial amounts within its trunk tissues (De Smedt et al., 2012; Theophilus and Jain, 2024). This internal reservoir not only supports the tree's survival under extended drought conditions but also contributes to moisture availability in the surrounding ecosystem (Deafalla, 2022). Other indigenous plants, including some wild legumes, display traits that enhance survival under drought conditions. While many of these adaptations, such as deep root systems and early flowering, are well known, tissue-level water storage remains underexplored in breeding programs (Doležal et al., 2021). *Tephrosia vogelii*, a leguminous species native to parts of West Africa, including Nigeria, has shown resilience in dry environments. Although it does not rely on water storage in the way succulent species do, it has been observed to maintain green foliage for a longer duration during dry periods. This may be due to efficient

water use and stress-tolerant physiology. Such traits could offer valuable insights for improving drought resilience in cultivated legumes.

Physiological Adaptations

Besides the structural modifications that enhance drought stress tolerance, many indigenous crops also exhibit physiological responses that help them withstand the stress. These responses function at the cellular and metabolic levels, enabling the plant to conserve energy and minimise water loss while also aiding in the essential activities necessary for its survival.

Stomatal Regulation

Stomatal regulation is one of the most effective physiological responses to drought. By adjusting stomatal conductance, plants can balance carbon intake with water conservation. This enables them to reduce water loss through transpiration during extreme drought stress while still keeping their photosynthetic activities alive.

- Cowpea (*Vigna unguiculata*) responds to heat by closing its stomata during the hottest parts of the day. This helps it minimise water loss without completely halting gas exchange (Tankari et al., 2021).
- Sorghum (*Sorghum bicolor*), on the other hand, uses a leaf-rolling mechanism, which not only helps it to conserve moisture that occurs as a result of transpiration but also creates a humid microenvironment around stomatal openings, which further slows down evaporation (Ndlovu et al., 2021).

These adaptations enhance crop resilience in rain-fed systems where irrigation is not a viable option and ensure a sustainable food production system despite climate variability.

Evolutionary Insights for Crop Improvement

Indigenous Crops

Certain indigenous crops have gradually developed traits that help them to survive drought. This does not happen by chance but as a result of many years of growing under harsh and unpredictable conditions (Sarma et al., 2024). These crops have been cultivated for centuries across Nigeria, especially in areas where the soils are low in nutrients and rainfall is limited (Asadu, 2015). Over time, they have adapted in ways that make them more tolerant of water stress (Basu et al., 2016), making them useful genetic resources for improving modern crop varieties (Salgotra and Chauhan, 2023).

Fonio (*Digitaria exilis*) is one of the oldest cereals grown in northern Nigeria (Ali and Teju, 2023). It can withstand drought partly because of its short life cycle, which allows it to reach maturity before the dry season becomes severe (Seleiman et al., 2021). Over time, this crop has adapted to make the best use of the short rainy seasons it receives (*Feedipedia*, n.d). It also makes efficient use of the water available in the soil, which further supports its survival in areas where rainfall is low and irregular (Bassi and Dugje, 2020).

Teff (*Eragrostis tef*), although mostly cultivated in Ethiopia, possesses drought-tolerant traits that are comparable to those found in certain drought-resilient grasses grown in Nigeria (Degu, Ohta and Fujimura, 2008). Through years of natural selection in its native dryland environments, teff has developed adaptations such as efficient water use and a fibrous root system that enables it to access moisture in the soil (Araya et al., 2011). These traits contribute to its resilience during long periods of drought. Its physiological characteristics could be studied and potentially incorporated into breeding programmes that are aimed at improving the drought tolerance of cereals cultivated in Nigeria.

These crops have not only developed resilient traits that enable them to survive under drought conditions, but they have also continued to produce food in regions where other crops struggle. The traits they have developed over multiple generations can be used to improve drought tolerance in widely grown crops like maize, rice, and sorghum. Unfortunately, the full potential of these indigenous crops is still largely underexplored in research and breeding programs, even though they hold the key to improving food security in Nigeria.

The broader implication of these findings is that natural selection has already carried out much of the work needed to develop resilience in crops, especially in regions like Nigeria that face repeated water stress. Traits such as drought-induced dormancy, deep root systems, and efficient stomatal behaviour have evolved as survival mechanisms, not just for persistence, but for reproduction and yield under challenging conditions. These same traits, if systematically incorporated into breeding programmes, could provide the foundation for developing crops that are both high-yielding and climate-resilient. Bridging the gap between evolutionary insights and formal breeding practice is therefore essential, not only for improving crop performance but also for strengthening food security in drought-prone regions where access to irrigation and inputs remains limited.

Genetic Diversity in Drought-Prone Regions

Regions that experience frequent droughts often harbour high genetic diversity in both cultivated and wild plant species. This diversity represents a crucial genetic reservoir for breeding crops with enhanced drought resilience.

Nigeria's indigenous crop varieties are shaped by centuries of natural selection and human cultivation, and they exhibit unique traits absent in many commercially bred hybrids (Azeez, Adubi and Durodola, 2018). These adaptive traits, often lost in industrial agricultural systems, are critical for future drought-tolerant adaptation.

Application of Gene Editing (CRISPR) and Molecular Breeding

Recent advancements in biotechnology, particularly in gene editing and molecular breeding, offer significant potential for enhancing drought resilience in crops. In Nigeria

specifically, the application of CRISPR-Cas9, marker-assisted selection, and genomic selection can help restore drought-tolerant traits to modern crops.

CRISPR-Cas9 technology offers a precise way to modify genes responsible for drought tolerance, such as those that control root depth, stomatal function, and water retention mechanisms (Joshi, Bharat and Mishra, 2020). This could help improve crops like maize and rice, which, although widely grown, are not resilient enough to withstand the erratic rainfall patterns common in Nigeria's climate (Zhu et al., 2023).

Marker-assisted selection (MAS) is another promising mechanism that can help to improve drought tolerance (Devi et al., 2017). It can be used to identify drought-tolerant traits in local landraces and then integrate them into high-yielding commercial crops. This ensures that while the yield remains high, the crops are also better equipped to cope with periods of water stress.

Genomic selection represents a significant advancement in plant breeding. It allows researchers to predict a plant's drought tolerance based on genome-wide DNA markers rather than waiting for the plant to fully mature and be tested under drought conditions. This approach accelerates the selection process and reduces the breeding cycle time; this enables faster development of improved drought-resilient varieties (Yoselin et al., 2023).

Despite these promising technologies, Nigeria faces challenges in fully adopting them. The country's agricultural sector still struggles with limited infrastructure, inadequate research funding, and a lack of sufficiently skilled personnel in molecular breeding (Naija Scholar, 2024b). To bridge this gap, significant investment in biotechnology and crop improvement research is needed. Such investment would help accelerate the development of drought-resilient crops, and this would ensure that the future of Nigeria's agriculture remains sustainable despite the growing climate challenges (Naija Scholar, 2024a).

Limitations of the Study

This review is based entirely on secondary data and existing literature; no original fieldwork or laboratory analysis was conducted. While the paper discusses drought-adaptive traits such as deep rooting, stomatal regulation, osmotic adjustment, and dormancy, these traits were not evaluated through direct molecular or physiological experiments. Instead, the review draws from peer-reviewed studies and empirical data to synthesise relevant findings within the Nigerian context.

Although the study highlights the evolutionary background of drought tolerance, it does not address the underlying genetic mechanisms or trace the lineage of specific traits in indigenous crop varieties. Similarly, while the role of traditional knowledge and community-level crop selection is acknowledged, it was not explored in depth. These areas represent valuable directions for future research. Empirical studies that validate these adaptive traits under field conditions and link them with local breeding efforts would further strengthen the practical application of the insights presented here.

Conclusion

This study highlights the need to move beyond short-term physiological responses when addressing drought tolerance in crops. While mechanisms like gene expression and osmoprotectant accumulation are important for understanding immediate stress responses, they do not fully account for how some crops have consistently survived under prolonged water scarcity over multiple growing seasons.

In Nigeria's arid and semi-arid regions, indigenous crops and their wild relatives have evolved a range of adaptive traits that support survival under extreme drought conditions. These include deep root systems that access water from deeper soil layers, efficient stomatal control that reduces water loss, and drought-induced dormancy that allows plants to endure harsh periods. Despite these traits, such crops remain underutilised in conventional breeding systems that tend to prioritise yield over resilience.

By bringing together insights from evolutionary biology, local adaptation, and breeding science, this review underscores the genetic value embedded in underutilised species. It also emphasises the need for conservation strategies that go beyond gene banks and support on-farm preservation, where adaptive traits can continue to evolve in line with environmental change.

As climate variability worsens, the path forward lies in rebalancing breeding priorities, developing crops that not only yield well under ideal conditions but also survive and perform under stress. This approach is essential to building long-term food security in Nigeria.

For breeders and policymakers, the main takeaway is clear: investing in the identification, conservation, and integration of naturally evolved traits into crop improvement programmes is no longer optional; it is a strategic necessity.

Recommendations

To effectively address drought-related challenges in Nigeria's agricultural systems, the following actions are recommended:

A. Research and Scientific Investigation

- Prioritise phylogenetic and comparative genomic studies to trace the evolutionary origins of drought tolerance in both cultivated crops and wild relatives.
- Identify conserved and divergent genetic markers that underpin long-term stress adaptation in Nigerian agroecological zones.
- Conduct empirical validation of drought-adaptive traits in indigenous crops under field conditions to bridge the gap between theory and application.

B. Conservation of Genetic Resources

- Strengthen the role of indigenous crops with naturally evolved drought resilience traits by ensuring their inclusion in national breeding strategies.
- Promote dual conservation strategies:
 - Ex situ, through expanded and well-maintained seed banks

- In situ, through on-farm preservation in collaboration with local farmers
- Empower and resource key institutions such as NACGRAB and NASC to lead these efforts sustainably.

C. Breeding Programme Innovation

- Shift breeding focus from short-term drought responses to long-term resilience without compromising yield.
- Integrate traits like deep root systems, osmotic adjustment, and drought-induced dormancy into elite varieties through genomic selection and marker-assisted breeding.
- Foster partnerships between public breeders, universities, and private sector actors to modernise and decentralise breeding processes.

D. Policy and Adoption Support

- Develop and enforce policy frameworks that incentivise the adoption of drought-resilient crop varieties, especially among smallholder and rain-fed farmers.
- Support capacity-building and knowledge dissemination through extension systems, helping farmers understand and adopt resilient varieties.

When evolutionary insights are integrated into crop improvement strategies, Nigeria and other drought-prone regions will be better positioned to develop sustainable, adaptive agricultural systems capable of withstanding future climate pressures.

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