

Genetic Diversity and Stress Tolerance in Nigerian Horticultural Crops: Multifactorial Influences and Breeding Implications

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Abstract

Horticultural crops matter more than they're often given credit for; especially in Nigeria, where they help feed families, support incomes, and offer some cushion against climate uncertainty. This review critically examines the genetic diversity of horticultural crops in Nigeria, emphasizing their role in nutrition, economic stability, and climate resilience. The objective is to synthesize current knowledge on genetic variation within staple vegetables (e.g., tomatoes, peppers, leafy greens) and fruits (e.g., mangoes, citrus) and how this diversity contributes to crop tolerance against biotic and abiotic stresses. A comprehensive literature survey was conducted, focusing on both phenotypic and molecular genetic studies in Nigerian horticultural species. Key findings reveal significant genetic variation that supports adaptation to drought, diseases, and poor soils, though this diversity is threatened by unregulated hybridization and scarce breeding investments. Stress response mechanisms are observed at multiple scales, from field-level symptoms reported by farmers to molecular changes such as gene expression modification and antioxidant activity. The review also evaluates modern breeding technologies, including gene editing and AI-driven predictive breeding, highlighting their potential when tailored to Nigeria's smallholder farming conditions and diverse agroecological zones. However, challenges persist due to limited infrastructure, fragmented data, and underfunded breeding programs. The conclusion advocates for integrating indigenous knowledge of resilient landraces with advanced genomics and establishing decentralized seed systems to safeguard crop diversity and enhance food security. Urgent coordinated research and investment are recommended to conserve vital genetic resources and ensure sustainable horticultural production under climate uncertainty in Nigeria.

Keywords: Horticultural Crops, Genetic Diversity, Stress Response, Gene Editing, AI Assisted Breeding, Food Security, Crop Breeding.

Introduction

Agriculture remains the backbone of Nigeria's economy, not merely in terms of GDP contribution, but more critically as a provider of livelihoods, food security, and rural stability. While staple crops such as cassava, maize, and rice often dominate policy discussions, the role of horticultural crops in Nigeria's broader agricultural landscape is far more significant than often recognized. Vegetables like tomato, pepper, okra, and leafy

greens such as fluted pumpkin and amaranth are not just sources of dietary micronutrients but are also vital for income generation, especially among smallholder farmers and women (Muazu & Rahman, 2024; Ngbede *et al.*, 2025; Brandon, 2025; Kainga & Johns, 2012; Aworh, 2015). These crops are grown across virtually every agroecological zone in Nigeria, from the humid rainforest belt of the south to the dry savannah regions in the north, adapting to a variety of soil, climatic, and socio-economic conditions.

Horticultural crops also play a crucial role in diversifying household nutrition and reducing the dependency on carbohydrate-based diets, a common feature of food insecurity in many Nigerian communities (Ahmed *et al.*, 2024). As urbanization expands and dietary preferences shift, the demand for fresh vegetables and fruits continues to rise. However, this demand is met with significant production constraints, ranging from climatic variability and pest infestations to poor access to improved seeds and market linkages (Saras *et al.*, 2023). The country's horticultural sub-sector remains underdeveloped, largely informal, and vulnerable to both biotic and abiotic stresses. The yield gaps between potential and actual output in many horticultural crops remain large, and this discrepancy is often attributed to genetic limitations, environmental stressors, and inadequate breeding interventions (Olukunle, 2013; Ibeawuchi *et al.*, 2015; Ipinmoroti *et al.*, 2023; Olejeme *et al.*, 2023).

It is within this context that the question of genetic diversity becomes urgent. Nigeria is blessed with a wide range of indigenous and adapted horticultural crop varieties, many of which have evolved under traditional cultivation systems. These landraces are often rich in genetic traits that could be harnessed to improve stress tolerance and productivity. However, the erosion of this diversity due to monocropping, urban encroachment, and reliance on a narrow set of commercial varieties poses significant risks to future resilience (Aremu & Akinwade, 2018).

Genetic diversity refers to the range of genetic characteristics found within and between plant species. It is a cornerstone of evolutionary resilience, providing a buffer against stresses such as disease outbreaks, climate shifts, and soil degradation. In the case of horticultural crops in Nigeria, diversity can manifest in varying levels of drought tolerance, pest resistance, nutritional composition, growth cycles, and even taste or texture preferences that influence consumer acceptance (Codjia *et al.*, 2023; Badu *et al.*, 2021; Lokko *et al.*, 2006). The interplay between genotype and environment, known as G×E interaction, is particularly pronounced in horticultural systems where crops are cultivated under diverse and often marginal conditions.

Unfortunately, systematic efforts to document, conserve, and improve this genetic base are still limited. Local seed systems dominate the horticultural sector, with farmers often saving seeds from year to year, leading to informal selection but also genetic bottlenecks (Uzoma *et al.*, 2023; Tessy *et al.*, 2022). Formal breeding programs, on the other hand, tend to focus on yield and shelf-life at the expense of other adaptive traits, resulting in varieties that may perform well in controlled trials but poorly in farmers' fields. The failure to fully integrate local knowledge and agroecological realities into breeding priorities has often

resulted in low adoption rates for so-called improved varieties (Oparinde *et al.*, 2016; Akanbi *et al.*, 2024).

Beyond the practical implications, the conservation of genetic diversity also holds cultural significance. Many indigenous vegetables such as “soko” (*Celosia argentea*) or “ugu” (*Telfairia occidentalis*) are embedded in local cuisines and medicinal practices, forming part of the social fabric of Nigerian communities (Dube *et al.*, 2018). Losing these varieties would not only be an agronomic setback but also a cultural loss.

One of the defining features of horticultural production in Nigeria is its exposure to a complex web of stress factors; both biotic (such as pathogens, pests, and weeds) and abiotic (such as drought, extreme temperatures, salinity, and nutrient-poor soils). These stressors often co-occur and interact in unpredictable ways, amplifying their overall impact on crop performance (Olowogbon *et al.*, 2019). For instance, temperature extremes can predispose crops to fungal infections, while drought conditions may exacerbate the impact of nematodes and insect pests.

Climate change has further complicated this landscape. Rising temperatures, erratic rainfall patterns, and increased frequency of extreme weather events have been linked to yield fluctuations and crop failures across various regions in Nigeria (Oghenekevwe & Adesoye, 2024). While some crops such as okra and pepper have innate drought-avoidance strategies, their effectiveness is often compromised under field conditions due to poor soil fertility, inadequate irrigation infrastructure, and pest pressure (Massrie, 2025; Kwajaffa *et al.*, 2015). These multifactorial influences are not merely additive; they are synergistic and require integrative responses at both the genetic and management levels.

Farmers’ adaptive strategies, including mixed cropping, staggered planting, and organic soil amendments, reflect an intuitive understanding of these stress interactions. However, such practices are often constrained by limited extension services, lack of timely weather forecasts, and restricted access to stress-tolerant planting materials (Okoronkwo *et al.*, 2015). Therefore, any meaningful intervention aimed at improving horticultural productivity must account for the complex ecological and socio-economic realities that farmers face on the ground.

Over the past decade, technological advancements in molecular biology and data science have begun to open new possibilities for addressing the long-standing challenges in Nigerian horticulture. Genomic selection, genome-wide association studies (GWAS), and CRISPR-based gene editing are increasingly being used to identify and manipulate genes responsible for traits such as heat tolerance, pest resistance, and nutrient use efficiency (Mcmillen *et al.*, 2022; Budhlakoti *et al.*, 2022). For example, recent work on tomato has pinpointed QTLs linked to drought resilience, which could be introgressed into local varieties to enhance field performance (Musa & Kolawole, 2024).

Artificial intelligence and machine learning tools are also being integrated into crop modeling and phenotyping platforms. These tools allow for more accurate predictions of how specific genotypes will respond to given environments, thereby enhancing the

efficiency of breeding programs (Gerakari *et al.*, 2025; Zhang *et al.*, 2024). Drones and remote sensing technologies are making it possible to collect real-time data on plant health, growth stages, and stress indicators, which can inform precision interventions at the farm level (Dulam *et al.*, 2025; Wang & Wang, 2024). While these innovations are still in their infancy in Nigeria, pilot projects in universities and research institutes show promising signs of scalability.

Nevertheless, the adoption of these technologies faces several bottlenecks, including high initial costs, lack of skilled personnel, and poor integration with traditional knowledge systems. Bridging this technological divide will require strategic investments, policy support, and capacity building, especially among the next generation of plant breeders and agronomists.

The urgency of strengthening Nigeria's horticultural sector cannot be overstated. With a population projected to reach over 377 million by 2050 (Gaines, 2023), food demand is set to increase dramatically. Meeting this demand sustainably will depend not only on boosting cereal yields but also on diversifying diets through increased consumption of fruits and vegetables. This shift will require horticultural crops that are resilient, nutritious, and adapted to local environments.

Despite the crucial role of horticultural crops in Nigeria's food security, livelihoods, and climate resilience, these crops have received disproportionately limited research and investment compared to major staples. There is a fragmented understanding of the genetic diversity present within Nigerian horticultural species and how this diversity contributes to stress tolerance. Furthermore, the integration of modern breeding technologies tailored to local farming contexts remains underexplored. This review seeks to fill these gaps by synthesizing existing knowledge on the genetic diversity of key Nigerian horticultural crops, drawing connections between genotype, environment, and management practices. It also highlights emerging technologies that could revolutionize breeding strategies and mitigate region-specific constraints.

Theoretical Framework for the Review

This review is grounded in a systems-based resilience framework, focusing on genotype × environment interactions and socio-ecological dimensions to analyze Nigerian horticultural crops. The resilience theory highlights how genetic diversity within landraces enhances adaptability to abiotic stresses such as drought, pests, and poor soils, shaped by farmer knowledge and natural selection over generations (Ogbu *et al.*, 2010; Sobowale *et al.*, 2020). Genotype × environment models clarify trait expressions across Nigeria's varying agroecological zones, underscoring the need for locally adapted breeding programs (Sobowale *et al.*, 2020; Aladele *et al.*, 2025). Indigenous horticultural genetic resources in Nigeria face threats from genetic erosion tied to unregulated hybridization and narrow breeding focus, urging conservation prioritization (Ogbu *et al.*, 2010; Aladele *et al.*, 2025). Integrating traditional farmer practices with genomic and biotechnological tools offers a

holistic approach for crop improvement and sustainability that can enhance food security under climate variability (Ogbu *et al.*, 2010; Aladele *et al.*, 2025; Sobowale *et al.*, 2020).

Methodological Approach for the Review

A systematic literature review was conducted using ResearchGate, PubMed, Scopus, and Google Scholar. Keywords such as "*Nigerian horticultural crops*," "*genetic diversity*," "*stress response/tolerance*," "*drought resistance*," and "*breeding technologies*" guided the search. Peer-reviewed articles published between 2005 and 2025 focusing on Nigerian horticultural species with data on genetic variation or stress responses were included. Studies unrelated to Nigeria or lacking primary genetic data were excluded.

After screening titles, abstracts, and full texts for relevance and quality, thematic analysis was used to synthesize findings on genetic diversity, stress tolerance mechanisms, and recent breeding advancements.

i. Genetic Diversity and Stress Tolerance

Genetic diversity is the cornerstone of crop adaptation and resilience in horticultural systems worldwide, particularly in Nigeria, where diverse environmental stressors such as drought, soil degradation, extreme temperatures, and pests threaten agricultural productivity (Khouri *et al.*, 2025; Tripathi *et al.*, 2015). Understanding the extent of genetic variation within Nigerian horticultural crops is critical for developing improved varieties that can withstand both biotic and abiotic stresses while maintaining yield stability (Chen *et al.*, 2016; Omondi *et al.*, 2016).

Nigeria, with its rich agro-ecological zones, from the humid rainforests of the south to the dry savannas of the north, provides a unique setting for studying genetic diversity in horticultural crops (Talucder *et al.*, 2024). The country's farming systems rely heavily on informal seed exchanges, local adaptation, and traditional knowledge, which contribute to the maintenance of landraces (Yolcu *et al.*, 2016; Onwe *et al.*, 2023). These landraces provide a valuable genetic reservoir that can be tapped into for breeding stress-tolerant crops suited to Nigeria's evolving climate challenges (Cortes & Lopez Hernandez, 2021).

Beyond traditional varieties, wild relatives of horticultural crops serve as an additional source of genetic diversity. Wild species often harbor genes linked to drought resistance, salinity tolerance, and pest resilience, making them indispensable for plant improvement efforts (Tanksley & McCouch, 1997; Hajjar & Hodgkin, 2007). For instance, studies on Nigerian tomato (*Solanum lycopersicum*) reveal that introgression of genes from wild relatives enhances heat and drought tolerance while maintaining fruit quality (Olaleken, 2024; Parisi *et al.*, 2020). Similarly, indigenous pepper (*Capsicum spp.*) varieties exhibit a wide range of genetic traits that influence pest resistance and adaptability to marginal soils (Olaleken, 2024).

Despite its importance, genetic diversity in Nigerian horticultural crops is declining due to factors such as intensive cultivation of commercial hybrids, loss of traditional farming practices, and environmental pressures (Khouri *et al.*, 2014; Tripathi *et al.*, 2015).

Conservation strategies, including seed banks, in situ preservation, and participatory breeding programs, are essential for sustaining genetic diversity and ensuring long-term food security (Yolcu *et al.*, 2016).

As Nigeria grapples with climate variability and an increasing demand for stress-resilient crops, leveraging genetic diversity through advanced breeding techniques, molecular studies, and genomic selection will be pivotal in enhancing agricultural sustainability (Chen *et al.*, 2016; Cortes & Lopez Hernandez, 2021). This section of this review explores the source of genetic diversity, stress response mechanisms, and growth-related genes and traits that influence horticultural crop performance in Nigeria, with a focus on bridging traditional breeding methods with modern biotechnological advances.

Where Genetic Diversity Comes From

Genetic diversity in Nigerian horticultural crops originates from traditional landraces, wild relatives, farmer-selected lines, and breeding programs. Nigeria's diverse agro-ecological zones, ranging from the humid rainforest to the dry savanna, contribute to the natural selection and adaptation of crops to different environmental conditions (Onwe *et al.*, 2023).

Traditional Landraces

Traditional landraces are locally adapted crop varieties that have been cultivated by Nigerian farmers for generations. These varieties exhibit high genetic variability, making them valuable for breeding programs (Khouri *et al.*, 2014). Nigerian farmers select seeds based on local adaptation and performance, ensuring the survival of stress-tolerant genotypes (Chen *et al.*, 2016). Landraces often possess unique genetic traits that enhance resistance to drought, pests, and diseases (Tripathi *et al.*, 2015). Also, the exchange of seeds among farmers contributes to genetic mixing, maintaining diversity within horticultural crops (Omondi *et al.*, 2016).

Studies on Nigerian tomato (*Solanum lycopersicum*) reveal that landraces exhibit superior drought tolerance compared to commercial hybrids, highlighting their importance in breeding programs (Yolcu *et al.*, 2016). Similarly, indigenous pepper (*Capsicum spp.*) varieties display genetic traits linked to pest resistance and adaptability to marginal soils (Cortes & Lopez Hernandez, 2021).

Wild Relatives and Natural Selection

Wild relatives of horticultural crops serve as genetic reservoirs for stress tolerance traits. These species often harbor genes linked to drought resistance, salinity tolerance, and pest resilience, making them indispensable for plant improvement efforts (Tanksley & McCouch, 1997; Hajjar & Hodgkin, 2007). For instance, wild tomato species possess genes that enhance heat and drought tolerance, which can be introgressed into cultivated varieties (Olaleken, 2024). Also, wild pepper species exhibit natural resistance to insect pests, reducing the need for chemical pesticides (Parisi *et al.*, 2020). Certain wild relatives of

Nigerian crops thrive in poor soils, offering genetic solutions for nutrient-deficient environments (Onwe *et al.*, 2023). Despite their importance, wild relatives are increasingly threatened by habitat destruction and climate change, necessitating conservation efforts to preserve their genetic potential (Khouri *et al.*, 2014; Tripathi *et al.*, 2015).

Farmer-Selected Lines and Informal Seed Systems

Nigerian farmers play a crucial role in maintaining genetic diversity by selecting seeds based on local adaptation and performance (Khouri *et al.*, 2014). Informal seed exchanges contribute to genetic variation, ensuring resilience against environmental stressors (Tripathi *et al.*, 2015). Farmers collaborate with researchers to identify stress-tolerant genotypes, integrating traditional knowledge with scientific advancements (Chen *et al.*, 2016). Also, local seed banks help preserve genetic diversity, ensuring the availability of stress-resistant varieties for future generations (Tanksley & McCouch, 1997).

Studies indicate that farmer-selected lines of Nigerian okra (*Abelmoschus esculentus*) exhibit superior drought tolerance, demonstrating the effectiveness of traditional selection methods (Oluwajobi *et al.*, 2024).

Breeding Programs and Genetic Engineering

Modern breeding programs and genetic engineering techniques have expanded the sources of genetic diversity in Nigerian horticultural crops. Some of these techniques include;

- ***Marker-Assisted Selection (MAS)***: MAS has been widely used to identify stress-tolerant genotypes in Nigerian horticultural crops (Chen *et al.*, 2016).
- ***CRISPR/Cas9 Gene Editing***: Recent studies highlight the potential of CRISPR/Cas9 technology in modifying stress-responsive genes to enhance tolerance in Nigerian crops (Chen *et al.*, 2016).
- ***Genomic Selection (GS)***: GS enables the prediction of stress tolerance traits based on genomic data, allowing breeders to select superior genotypes efficiently (Cortes & Lopez Hernandez, 2021).

Despite its potential, genetic engineering faces challenges related to regulatory policies, farmer adoption, and ethical concerns, necessitating further research and policy development.

How Crops Handle Stress

Nigerian horticultural crops are frequently exposed to environmental stressors such as drought, pests, poor soil conditions, and extreme weather events, which significantly impact their growth, yield, and survival (Khouri *et al.*, 2014; Tripathi *et al.*, 2015). The ability of crops to withstand these challenges depends on their physiological, biochemical, and molecular responses, which have evolved over time or have been enhanced through breeding programs (Chen *et al.*, 2016). Understanding these mechanisms is crucial for

developing resilient crop varieties that can sustain agricultural productivity in Nigeria's diverse agro-ecological zones (Yolcu *et al.*, 2016; Cortes & Lopez Hernandez, 2021)

Physiological Adjustments to Stress

Plants employ various physiological mechanisms to cope with environmental stressors, ensuring survival and continued productivity. These adaptations include drought tolerance mechanisms, water conservation strategies, nutrient uptake modifications, salinity resistance, heat stress adaptation, and structural changes that enhance resilience (Onwe *et al.*, 2023).

- **Drought Tolerance Mechanisms:** Drought is one of the most significant threats to Nigerian horticultural crops, particularly in the northern regions, where rainfall is scarce (Khoury *et al.*, 2014). Crops have developed several physiological responses to mitigate water loss and maintain cellular function. Some Nigerian crops, such as cassava (*Manihot esculenta*) and sorghum (*Sorghum bicolor*), develop deep and extensive root networks to access underground water reserves (Tripathi *et al.*, 2015). Plants like okra (*Abelmoschus esculentus*) reduce water loss by rolling their leaves and closing stomata during periods of drought (Chen *et al.*, 2016). Additionally, certain crops synthesize Osmo-protectants such as proline, glycine betaine, and sugars, which help maintain cellular hydration under water-deficient conditions (Omondi *et al.*, 2016).
- **Salinity Resistance:** Soil salinity is an emerging challenge in Nigerian agriculture, particularly in coastal and irrigated regions (Yolcu *et al.*, 2016). Some crops have developed physiological mechanisms to tolerate high salt concentrations. For instance, Nigerian tomato (*Solanum lycopersicum*) and pepper (*Capsicum* spp.) regulate sodium and potassium transport to prevent toxicity (Cortes & Lopez Hernandez, 2021). Certain plants, such as mangrove-associated crops, actively exclude excess salt through specialized root structures (Khoury *et al.*, 2014). Furthermore, salinity stress induces oxidative damage, but crops like cowpea (*Vigna unguiculata*) produce antioxidants to neutralize harmful reactive oxygen species (Tripathi *et al.*, 2015).
- **Heat Stress Adaptation:** Rising temperatures due to climate change pose a serious threat to Nigerian horticultural crops (Parisi *et al.*, 2020). Heat stress affects photosynthesis, enzyme activity, and water retention, leading to reduced yields. Some adaptive responses include the production of heat shock proteins (HSPs) in crops such as yam (*Dioscorea* spp.), which protect cellular structures from heat-induced damage (Chen *et al.*, 2016). Certain Nigerian crops develop thicker cuticles through wax deposition on leaves to reduce transpiration and prevent excessive water loss (Onwe *et al.*, 2023). Additionally, plants like maize (*Zea mays*) adjust their leaf angles to minimize direct exposure to intense sunlight (Yolcu *et al.*, 2016).

2.2.2 Biochemical and Molecular Responses to Stress

At the cellular level, Nigerian horticultural crops activate biochemical pathways and gene expression changes to counteract environmental stressors (Parisi *et al.*, 2020). These responses involve stress-related proteins, secondary metabolites, and epigenetic modifications that enhance resilience.

- i. **Gene Expression Changes Under Stress:** Plants regulate gene expression to activate defense mechanisms when exposed to drought, salinity, or extreme temperatures (Khoury *et al.*, 2014). Key genes involved in stress tolerance include dehydration-responsive element-binding (DREB) genes, which regulate drought-responsive pathways, improving water retention in crops like cassava and sorghum [35][Tripathi *et al.*, 2015]. MYB transcription factors enhance salt resistance by controlling ion transport and osmoprotectant synthesis in tomato and pepper (Chen *et al.*, 2016). Additionally, heat shock protein (HSP) genes protect cellular structures from temperature-induced damage, ensuring survival during heat waves (Omondi *et al.*, 2016).
- ii. **Secondary Metabolites and Antioxidants:** Plants produce secondary metabolites to counteract stress-induced damage and deter pests (Yolcu *et al.*, 2016). Nigerian crops like cocoa (*Theobroma cacao*) synthesize flavonoids, which act as antioxidants to neutralize oxidative stress (Cortes & Lopez Hernandez, 2021). Certain indigenous pepper varieties produce alkaloids, which deter insect pests and reduce crop damage (Khoury *et al.*, 2014). Additionally, crops such as cowpea accumulate polyamines, which stabilize cellular membranes under drought and salinity stress (Tripathi *et al.*, 2015).
- iii. **Epigenetic Modifications and Stress Memory:** Recent studies highlight the role of epigenetic modifications in stress tolerance, allowing crops to “remember” previous stress exposures and respond more effectively in future conditions (Chen *et al.*, 2016). DNA methylation alters gene expression patterns to enhance drought and heat tolerance (Omondi *et al.*, 2016). Histone modifications regulate chromatin structure, influencing stress-responsive genes (Yolcu *et al.*, 2016). Furthermore, microRNAs (miRNAs) modulate gene activity, improving resilience in crops like tomato and maize (Cortes & Lopez Hernandez, 2021).

Growth-Related Genes and Traits in Nigerian Horticultural Crops

Horticultural crops don't just grow by chance; their development is shaped by a mix of genetics, hormones, and environmental factors. These elements work together to influence everything from yield and stress resistance to how well a crop adapts to its surroundings (Khoury *et al.*, 2014; Tripathi *et al.*, 2015). In Nigeria, where farming conditions vary widely, unlocking the genetic secrets behind plant growth is key to boosting productivity and resilience (Chen *et al.*, 2016; Omondi *et al.*, 2016). Thanks to breakthroughs in molecular breeding and gene editing, scientists are now pinpointing the exact genes that drive plant

development; opening doors for smarter, more efficient horticulture in Nigeria (Yolcu *et al.*, 2016; Cortes & Lopez Hernandez, 2021).

Genetic Regulation of Growth

When it comes to plant growth, genes are the ultimate blueprint. They dictate everything from how tall a plant grows to when it flowers, how its roots spread, and even the size of its fruits (Onwe *et al.*, 2023). But genes don't work alone; hormones and environmental cues also play a big role, fine-tuning growth to suit Nigeria's unique conditions (Khoury *et al.*, 2014).

Take yield, for example. It's one of the most critical traits for farmers, and certain genes have a direct hand in fruit size, seed quality, and overall biomass (Tripathi *et al.*, 2015). Among these are gibberellin (GA) genes, which help regulate stem growth and fruit development in crops like tomatoes and peppers (Chen *et al.*, 2016). Another group, the AP2/ERF transcription factors, control flowering and ripening, ensuring plants can handle stress while still producing high yields (Omondi *et al.*, 2016). Then there are the SPL genes, which influence how crops like cassava and yam grow and reproduce (Yolcu *et al.*, 2016).

Roots are just as important; especially in Nigeria, where poor soil quality can make farming a challenge. The right root structure helps plants absorb nutrients, resist drought, and thrive in tough conditions (Cortes & Lopez Hernandez, 2021). Auxin Response Factors (ARFs), for instance, help roots grow longer and branch out, which is crucial for crops like cowpea (Khoury *et al.*, 2014). Meanwhile, NRT genes boost nitrogen uptake, and MYB transcription factors improve phosphorus absorption; both vital for healthy growth in nutrient-starved soils (Tripathi *et al.*, 2015; Chen *et al.*, 2016).

How Hormones Shape Growth in Nigerian Crops

Hormones are like the plant's internal messaging system, coordinating growth, stress responses, and key life stages (Yolcu *et al.*, 2016). In Nigeria's variable climate, these hormonal signals help crops adjust and perform at their best (Cortes & Lopez Hernandez, 2021). Auxins, for example, are essential for root development and fruit formation. Proteins like PIN-FORMED (PIN) ensure auxins are distributed properly, guiding how roots and shoots develop in crops like cassava and yam (Khoury *et al.*, 2014). YUCCA genes, on the other hand, help produce auxins, promoting leaf growth and fruit set in tomatoes and peppers (Tripathi *et al.*, 2015).

Cytokinins are another key player; they regulate cell division, delay aging in leaves, and help plants make the most of available nutrients (Chen *et al.*, 2016). Receptors like CRE1/AHK enhance shoot growth in cowpea and okra, while the LOG gene ensures cytokinins are produced in just the right amounts for flowering and fruiting (Omondi *et al.*, 2016; Yolcu *et al.*, 2016). And let's not forget gibberellins; the hormones behind stem elongation and flowering. Genes like GA20ox and GA3ox control gibberellin levels, affecting everything from bloom time to fruit size (Omondi *et al.*, 2016). Meanwhile, DELLA proteins act as a natural brake, keeping growth balanced even under stress (Omondi *et al.*, 2016).

Smarter Breeding with Genomics and Gene Editing

Modern breeding is no longer just guesswork; it's a precise science. Thanks to genomic selection and gene editing, researchers can now fast-track improvements in Nigerian horticultural crops (Chen *et al.*, 2016). Marker-assisted selection (MAS) is one powerful tool. By linking specific genes to traits like yield and drought resistance, breeders can pick the best plants more efficiently (Omondi *et al.*, 2016). For example, SNP markers help identify high-yielding tomato and pepper varieties, while QTL mapping reveals which genes control root depth in cassava and yam (Omondi *et al.*, 2016).

Then there's CRISPR/Cas9, a game-changer in crop improvement. This gene-editing technology allows scientists to tweak growth-related genes with incredible precision (Olaleken, 2024). Editing GA genes, for instance, can lead to earlier flowering and higher productivity (Chen *et al.*, 2016; Olaleken, 2024). Adjusting auxin pathways, on the other hand, can enhance root growth; a major advantage in poor soils (Khoury *et al.*, 2014).

Genomic selection (GS) takes things even further. By analyzing a plant's entire genetic makeup, breeders can predict how it will perform before it even grows (Olaleken, 2024). Machine learning models are now being used to refine these predictions, while epigenetics; the study of how environment affects gene expression, helps scientists understand how crops "remember" stress and adapt over time (Yolcu *et al.*, 2016; Cortes & Lopez Hernandez, 2021).

Environmental Factors that Affect Crop Growth

Non-Biological (Abiotic) Stressors

Agriculture in Nigeria is no stranger to adversity, but among the many challenges facing the sector, abiotic stressors have emerged as some of the most quietly disruptive forces impacting horticultural productivity. Unlike biological threats; such as pests or pathogens, which can often be addressed through resistant varieties or targeted interventions, abiotic stressors are broader in scale and less predictable. Environmental pressures like erratic rainfall, rising temperatures, soil degradation, and salinity tend to operate in complex, interconnected ways, affecting not just yield but also the long-term viability of horticultural systems. In a country with such a broad spectrum of agroecological zones, the consequences of these stressors vary widely, yet remain consistently severe.

One of the most pressing issues today is the increasing irregularity of rainfall. For generations, smallholder farmers across Nigeria have relied on seasonal rain patterns to guide planting and harvesting. That rhythm, however, has become unreliable. In the northern regions; particularly the Sahel and savannah belts, rain now tends to fall in short, intense bursts, followed by extended dry spells (Panthou *et al.*, 2020; Salami, 2024). This pattern creates an unforgiving cycle of waterlogging and drought, both of which can devastate crops like tomatoes, peppers, and onions. Meanwhile, the southern zones have experienced prolonged rainy seasons with heavier downpours, leading to frequent flooding and accelerated nutrient loss through leaching (Onefeli *et al.*, 2023). These shifting patterns

have made planning and crop management much more complicated, often turning routine seasons into risky ventures.

The consequences of these fluctuations are far-reaching. When dry spells extend for weeks, evapotranspiration increases sharply, placing immense water stress on crops especially those rooted in sandy or shallow soils that can't retain moisture effectively (Shanono *et al.*, 2023; Edebeatu *et al.*, 2025). The physiological effects of this water stress manifest quickly: diminished photosynthesis, delayed flowering, lower fruit set, and reduced overall biomass. Even crops traditionally considered hardy, like okra, have shown noticeable declines in yield under these conditions (Abdulrahman & Nahir, 2018). On the other hand, excessive rainfall can flood root zones, suffocating plants and creating ideal conditions for root rot and fungal infections. Crops such as ginger and sweet potato are particularly vulnerable, as their root systems are not equipped to handle prolonged saturation (Hossain, 2025).

Beyond rainfall, soil degradation poses another critical challenge. Many Nigerian soils especially those subjected to continuous cultivation in peri-urban vegetable farms are showing signs of fatigue. Years of harvesting without adequate replenishment have led to nutrient depletion, particularly of nitrogen, potassium, and magnesium (Omotay & Chukwuka, 2009; Ibeawuchi *et al.*, 2015; Alhassan *et al.*, 2021). These deficiencies compromise plant health and reduce the capacity of crops to withstand other environmental pressures. Compacted soils, erosion-prone surfaces, and declining organic matter are increasingly common, especially in transition zones between forest and savannah. In these areas, root penetration becomes difficult, limiting access to deeper moisture and essential nutrients, which further weakens plants during critical growth stages (Alhassan *et al.*, 2021).

Adding to this burden is the creeping threat of salinity, particularly in coastal zones and low-lying inland valleys. While irrigation is a potential solution to drought, it brings its own risks; especially when groundwater or poorly drained systems are involved. Repeated irrigation without adequate leaching can lead to the buildup of salts in the root zone, disrupting the osmotic balance in plant cells and reducing water uptake (Abubakar & Gahsua, 2024; Sani *et al.*, 2024; Owonubi & George, 2019). In areas like Lagos and parts of the Niger Delta, vegetable farmers have reported yield losses in sensitive crops like fluted pumpkin (*Telfairia occidentalis*) due to salt stress (Amuyi & Nweke, 2022). Sodium and chloride toxicity, which often accompany saline conditions, can be lethal even at moderate concentrations, particularly for leafy vegetables and fruit crops.

High temperature stress is yet another growing concern, particularly in Nigeria's central and northern regions. Over the past decade, average daytime temperatures have risen steadily, with heatwaves becoming more frequent and prolonged (Agada & Yakubu, 2022; Igbawua & Jande, 2023). For many horticultural crops, temperatures above 35°C pose a serious risk to reproductive development (Razzaq *et al.*, 2019). Crops like cucumber, pepper, and onion often experience flower drop, pollen sterility, and poor fruit formation under extreme heat conditions. Unlike soil or water-related stress, high temperature affects multiple physiological systems at once; photosynthesis, respiration, hormonal regulation making it

one of the hardest stressors to manage through simple agronomic practices (Wahid *et al.*, 2007; Zhao *et al.*, 2017).

What makes the abiotic stress landscape particularly complex in Nigeria is the way these stressors tend to overlap and compound each other. Farmers in the southeast, for instance, often struggle with excess rainfall and soil erosion, while their counterparts in the arid northwest are more concerned with moisture conservation and protection from scorching winds (Wahab *et al.*, 2020). This regional variation calls for localized, adaptive strategies rather than blanket solutions. Attempting to apply the same approach across all regions often fails to address the specific environmental realities that farmers face on the ground. Moreover, when multiple stressors occur simultaneously, their combined effects are often worse than each stressor alone. Heat, for instance, can intensify the impact of drought by increasing evaporation rates and depleting already scarce soil moisture. Similarly, degraded soils with poor structure and low organic content are less capable of buffering against salinity, making salt buildup more damaging (Negacz *et al.*, 2022; Etesami & Noori, 2019; Kayode *et al.*, 2021). In these complex stress environments, crops often display a variety of symptoms such as wilting, leaf scorching, and poor fruit development which complicate both accurate diagnosis and timely intervention.

Horticultural crops, by nature, are especially sensitive to such disruptions. Most are grown for fresh consumption and have short growth cycles, narrow optimal climate windows, and specific nutrient requirements. Even short-term exposure to stress can lead to visible and economic losses. For smallholder farmers, these losses go beyond the farm gate. Reduced yields translate directly into lower household income and food insecurity, especially when no safety nets are in place (Ojo *et al.*, 2024).

But yield isn't the only thing at risk. Abiotic stress also affects the nutritional value of crops. Studies have shown that conditions like drought and salinity can alter nutrient uptake, reduce the concentration of key vitamins and minerals, and affect the taste and marketability of fresh produce (Hu & Schmidhatter, 2025; Ehtaiwesh, 2022). For instance, tomatoes and leafy greens grown under stress often contain less vitamin C and iron nutrients already in short supply in many Nigerian diets (Rouphael & Colla, 2025; Kaus & Kapoor, 2001). Stress can also lower sugar content and the accumulation of flavor-enhancing phytochemicals, making produce less appealing to consumers (Kaus & Kapoor, 2001).

In the face of these challenges, both farmers and institutions are beginning to adapt. In the northern regions, for example, mulching and the use of shade nets are becoming more common. These practices help conserve soil moisture and reduce heat stress on delicate crops (Iqbal *et al.*, 2020; Yusef *et al.*, 2025). In flood-prone areas, raised-bed cultivation and improved drainage systems are proving effective in reducing root-zone saturation. However, while these techniques show promise, they often require additional labor or upfront investment, making them difficult to adopt for resource-constrained farmers.

On the research front, plant scientists and breeders are actively working to identify genotypes with improved tolerance to abiotic stress. Screening efforts on tomato landraces, for example, have revealed several promising varieties with stronger root systems and more efficient water-use characteristics (Grozeva *et al.*, 2024). Biochar, compost, and other organic soil amendments are also being explored as ways to improve soil structure and water retention, especially in drought-prone areas like the northeast (Wu *et al.*, 2023). These approaches represent a step in the right direction, but their effectiveness will depend on sustained support, training, and access.

Despite all these efforts, the bigger picture remains sobering. Climate projections suggest that if warming trends continue unchecked, many parts of Nigeria's middle-belt may become marginal or unsuitable for key horticultural crops by the middle of this century (Ilesanmi *et al.*, 2024). This isn't just a climate issue; it's a development issue that demands coordinated responses. Public policy, research, infrastructure, and extension services must come together in new ways to help Nigeria's horticultural sector adjust to these new environmental realities.

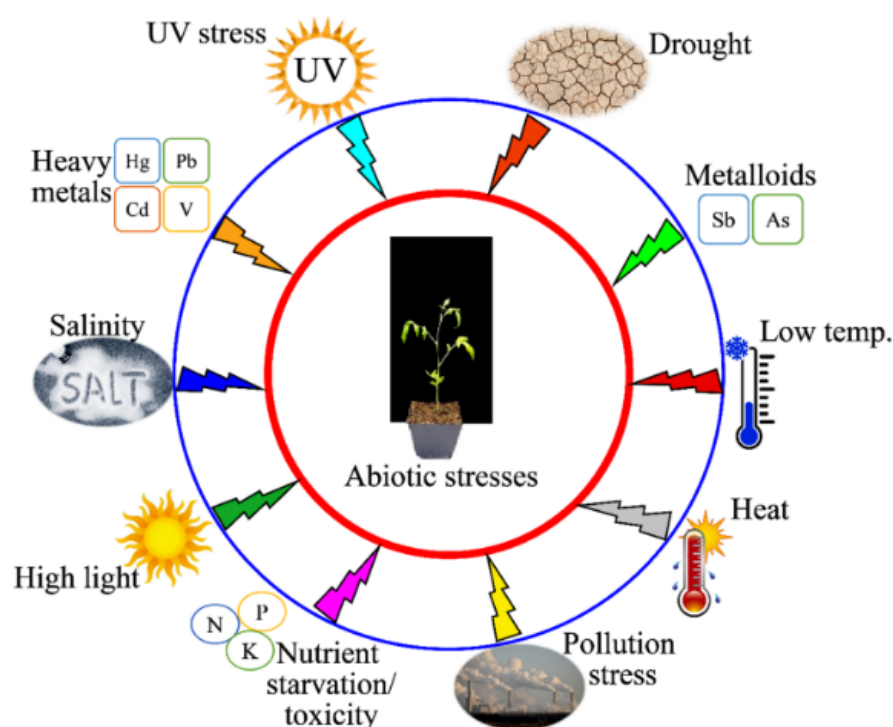


Fig. 1. Visual representation of different environmental stressors that impair the healthy growth and development of horticultural crops.

Source: Altaf *et al.*, 2023

Table 1: Major Abiotic Stressors Affecting Horticultural Crops in Nigeria by Region

Abiotic Stressor	Predominant Region(s)	Affected Crops	Observed Impact on Crops	References
Irregular Rainfall	North Central, North East	Tomato, Pepper, Okra	Wilting, reduced fruit set, poor seed germination due to drought or waterlogging	Onefeli <i>et al.</i> , 2023; Salami, 2024
High Temperature	North West, North Central	Onion, Cucumber, Tomato	Pollen sterility, flower drop, accelerated senescence, poor tuber formation	Agada & Yakubu, 2022; Igbawua & Jande, 2023
Soil Degradation	South West, North Central	Fluted Pumpkin, Amaranth, Garden Egg	Stunted growth, chlorosis, low nutrient uptake, soil compaction	Ibeawuchi <i>et al.</i> , 2015; Alhassan <i>et al.</i> , 2021
Salinity	Coastal (Lagos, Delta), South Niger Inland Valleys	Telfairia, Spinach, Tomato	Leaf burn, ion toxicity (Na ⁺ , Cl ⁻), osmotic stress, reduced root absorption capacity	Amuyi & Nweke, 2022
Flooding	South East, South South	Sweet Potato, Leafy Greens, Ginger	Root rot, stem lodging, nutrient leaching, delayed maturity	Onefeli <i>et al.</i> , 2023

The table captures the most prominent non-biological (abiotic) stressors affecting Nigerian horticultural production and links them to specific regions, crop types, and physiological or yield-related outcomes. Its primary function is to map the spatial variability of stress factors across Nigeria's agroecological zones, thereby reinforcing the idea that localized solutions are essential.

Living Threats: Pests and Diseases

The productivity and long-term sustainability of Nigeria's horticultural landscape are increasingly compromised by the persistent onslaught of biotic stressors. These threats, which include insect pests, fungal pathogens, viruses, and parasitic weeds, are not only disruptive to crop physiology but also erode the economic potential of horticultural farming, both for subsistence and commercial growers. As Nigeria continues to grapple with food insecurity, understanding the multifaceted nature of biotic stress becomes

essential for designing locally appropriate mitigation strategies and bolstering genetic resistance in crop breeding initiatives.

Insect Pests: A Dynamic and Evolving Threat

Insect pests remain a dominant force undermining horticultural productivity across Nigeria's diverse agroecological zones. Among the most alarming is *Tuta absoluta*, a destructive leaf miner of tomato crops. This invasive pest, originally native to South America, has in recent years established itself firmly in West Africa, with reports indicating yield losses reaching 100% in unmanaged fields (Tarusikirwa *et al.*, 2020). Its resilience and rapid reproductive cycle, coupled with increasing resistance to synthetic insecticides, have made it particularly difficult to control.

Equally notorious are flea beetles (*Podagrica spp.*), which target okra crops by defoliating leaves and disrupting early-stage growth, leading to reduced marketable yield (Ofuya *et al.*, 2023). In pepper farms across the humid south and the northern savannah, the whitefly (*Bemisia tabaci*) continues to wreak havoc; not only through direct sap extraction but more critically as a vector for devastating plant viruses such as Pepper Veinal Mottle Virus and Tomato Yellow Leaf Curl Virus (Abubakar *et al.*, 2022). The role of whiteflies in amplifying viral incidence presents a dual threat that complicates management practices.

Another recurrent pest is the African armyworm (*Spodoptera exempta*), which thrives during the wet season. Characterized by its outbreak dynamics and aggressive migratory behavior, this caterpillar species inflicts broad-spectrum foliar damage, particularly on leafy vegetables and young seedlings (Odeyemi & Ugwu, 2021). For smallholder farmers, especially those without access to early warning systems or bio-rational control tools, outbreaks can mean total crop failure.

Fungal Pathogens: Silent Destroyers

Fungal infections are perhaps less immediately visible than insect damage, yet they account for significant annual losses in horticultural outputs across the country. Soil-borne fungi such as *Fusarium oxysporum*, *Rhizoctonia solani*, and *Macrophomina phaseolina* are frequently encountered in vegetable fields and are responsible for diseases like root rot, stem cankers, and wilting (Terna *et al.*, 2017; Pothiraj *et al.*, 2021). These pathogens have a capacity for long-term survival in the soil, even in the absence of a host, thereby posing a chronic risk to crop rotation systems.

For example, studies conducted in Adamawa's Gerio Irrigation Scheme revealed a high prevalence of pathogenic fungi such as *Sclerotinia sclerotiorum* and *Alternaria alternata*, which affect tomatoes, chili peppers, and cucumbers (Akinde *et al.*, 2018; Zakari *et al.*, 2021). Their persistence in warm, humid conditions; typical of Nigeria's middle belt and southern regions makes conventional fungicide application insufficient. Moreover, resistance to commonly used fungicides is on the rise, necessitating a pivot towards integrated strategies combining host resistance, crop hygiene, and soil health management (Mendoza-de, 2022).

Viral Diseases: Invisible Threats

Unlike insect and fungal infestations that often produce conspicuous symptoms, viral infections in horticultural crops typically remain unnoticed until yield losses become economically damaging. Among the most prevalent viral diseases in Nigeria is the Pepper Leaf Curl Virus (PepLCV), which causes chlorosis, leaf curling, and severe stunting, especially in hot, humid regions (Ekpiken & Eyong, 2024; Parisi *et al.*, 2020). The vector, *Bemisia tabaci*, exacerbates this problem by enabling viral transmission over wide distances. The Chilli Leaf Curl Virus (ChiLCV) and the Tomato Yellow Leaf Curl Virus (TYLCV) are also increasingly reported in vegetable belts across Lagos, Oyo, and Kano states (Abraham *et al.*, 2021; Roy *et al.*, 2023). These infections distort plant morphology and lead to fruit deformation, rendering them unsuitable for sale. One of the most troubling aspects of viral pathogens is their capacity for genetic recombination and rapid strain evolution, which outpaces traditional breeding responses (Seal & Vanden Bosch, 2006).

Efforts to manage viral infections have so far emphasized vector control and the development of resistant cultivars. Yet, in the absence of widespread diagnostic facilities and surveillance systems, early detection remains a persistent challenge.

Parasitic Weeds: The Silent Invaders

Parasitic weeds, particularly *Striga hermonthica* and *Striga asiatica*, have long been associated with cereal crops, but their encroachment into horticultural fields is becoming increasingly documented. These root-parasitizing plants siphon off nutrients and water from their hosts, drastically reducing crop vigor and yield (Parker, 2013). The infestation is especially severe in sandy and low-fertility soils, common in the semi-arid regions of the north.

What makes *Striga* particularly insidious is its prolific seed production; each plant capable of producing up to 50,000 seeds and its remarkable seed dormancy, which allows it to persist in soil for decades. Integrated management approaches, including intercropping with trap crops, soil solarization, and the application of organic matter, have shown varying degrees of success (Achmon *et al.*, 2017). However, the scale of infestation continues to outpace these localized interventions.

Complexities of Management and Emerging Resistance

Managing biotic stressors in Nigeria's horticultural systems is complicated by a host of socio-economic and infrastructural limitations. Many smallholder farmers still rely heavily on recycled seeds lacking resistance traits, which increases vulnerability to pests and diseases (Lucas, 2011). The widespread availability and aggressive marketing of synthetic pesticides have also led to unsustainable application patterns, resulting in pesticide resistance; particularly in *Tuta absoluta* and *Bemisia tabaci* populations (Bala *et al.*, 2019; Houndete *et al.*, 2010).

In addition, poor extension support and limited farmer education contribute to the underutilization of integrated pest management (IPM) strategies. This gap between research outputs and on-farm application remains a critical bottleneck in Nigeria’s quest for resilient horticultural systems.

Table 2: Biotic stress Factors Affecting Horticultural Crops

Stress Factor	Examples	Effects on Crops	References
Insects	<i>Tuta absoluta</i> <i>Podagrica spp.</i> <i>Bemisia tabacci</i> <i>Spodoptera exempta</i>	Significant yield losses Defoliation afeeding damage Transmission of viral pathogens	Tarusikirwa <i>et al.</i> , 2020; Ofuya <i>et al.</i> , 2023; Abubakar <i>et al.</i> , 2022; Odeyemi & Ugwu, 2021
Fungi	<i>Fusarium spp.</i> <i>Rhizoctonia solani</i> <i>Macrophomina phaselina</i> <i>Sclerotinia spp.</i>	Root-rot, Damping-off diseases Yield reduction	Pothiraj <i>et al.</i> , 2021; Akinde <i>et al.</i> , 2018; Zakari <i>et al.</i> , 2021
Viruses	Pepper leaf curl virus Chilli leaf curl virus Tomato spotted wilt virus	Leaf curling, Necrosis, Fruit deformation, Yield losses	Ekpiken & Eyong, 2024; Roy <i>et al.</i> , 2023; Abraham <i>et al.</i> , 2021
Weeds	<i>Striga spp.</i>	Nurient and water depletion, Stunted growth and decreased crop viability	Parker, 2013; Achmon <i>et al.</i> , 2017

The table provides a clear illustration of the key biotic stressors impacting Nigerian horticultural crops. It categorizes these factors into four broad groups: insects, fungi, viruses, and weeds. Each stress factor is accompanied by specific examples and an outline of its effects on crops.

Genotype Meets Environment

Nigeria’s landscape is remarkably varied ranging from humid coastal zones to arid savannas and this diversity poses both a challenge and an opportunity for agricultural production. The relationship between genotype and environment (commonly referred to as G × E interaction) becomes particularly important when evaluating the performance of horticultural crops. While it might seem intuitive that climate and soil matter, what’s often less appreciated is how significantly they influence the way a given genotype behaves from one region to another. A crop that performs well in the fertile, rain-fed regions of the south may not replicate that success under the drier or more nutrient-poor conditions found elsewhere in the country.

The concept of G × E interaction captures this variability in performance. Essentially, it describes the uneven expression of genetic traits across different environmental contexts.

In Nigerian horticulture, several factors come into play; temperature shifts, differences in soil composition, seasonal rainfall patterns, and even the prevalence of pests and diseases. All of these can shape how a crop grows and yields. For example, one variety might tolerate drought better than another, but only when grown in certain soil types or under specific management practices. This complexity means that breeding programs can't rely on uniform results from genotype trials alone. They need to pay close attention to how genotypes respond to real-world conditions. Without that, there's a real risk of recommending varieties that fail to deliver consistent results once they leave the controlled environment of test plots.

Case Studies of $G \times E$ Interactions in Nigerian Horticultural Crops

In Nigeria, where climatic and ecological zones vary widely even across short distances, genotype $\times$ environment ($G \times E$) interaction is more than just a statistical curiosity; it's a serious factor shaping agricultural outcomes. This has become particularly evident in horticultural crops, where performance in one location often fails to replicate elsewhere, no matter how promising a genotype may appear at first glance.

The findings from the study by Popoola *et al.*, (2024), which examined 42 elite cowpea genotypes grown across five Nigerian agroecological zones; Ibadan, Shika, Bauchi, Bagauda, and Gumel during the 2021 growing season explains that not only were the $G \times E$ interactions significant, but the differences in performance were sometimes stark. Interestingly, the genotypes G21 (IT14K-2111-2) and G25 (IT15K-2386-1) consistently produced high yields across all the test locations, suggesting they possess a wide range of adaptability. On the other hand, certain genotypes such as G41 (IT11K-61-82), G30 (IT16K-2365-1), and G5 (245-1) stood out in specific environments; Ibadan and Shika for G41, Bauchi for G30, and Bagauda and Gumel for G5 (Popoola *et al.*, 2024). This kind of pattern shows just how crucial it is to test widely before drawing conclusions about a variety's potential.

In another case, researchers looked at Bambara groundnut, which is often considered a climate-resilient crop. Yet, even with its reputation for drought tolerance, its growth and yield parameters shifted noticeably depending on the agroecological zone (Olanrewaju *et al.*, 2021). What this means in practical terms is that the crop's morphological traits aren't as stable as one might hope; they're still very much shaped by the surrounding environment. That's important for breeders to consider, especially when targeting dry zones.

There's also interesting work on cassava, particularly regarding its response to nitrogen. In a multi-site evaluation under both low and optimal nitrogen levels, some genotypes kept up decent yields regardless of nutrient input. Others, however, were clearly dependent on higher nitrogen availability (Maroya *et al.*, 2013). In a country where fertilizer use can be inconsistent or unaffordable, genotypes that tolerate low-nitrogen soils could be a game-changer for smallholders (Uba & Nwobi, 2022).

Okra, too, has had its moment under the microscope. One evaluation, which involved 29 accessions across four regions, found that seed yield was strongly influenced by both the genotype and the growing environment. While a few accessions maintained their performance over time and space, others didn't; meaning they might only be suitable for very specific regions or seasons (Nwangbunka *et al.*, 2011). That's the kind of insight that can save farmers from planting something that won't deliver under their local conditions. Then there's cucumber, which was tested in four different environments within Cross River State. Here, researchers leaned on statistical tools like AMMI and GGE biplot analysis to make sense of the results. These methods helped to tease apart which genotypes were genuinely stable and high-yielding versus those that only did well in one location. The implications simply stated that location matters a lot (Iwo & Odor, 2018).

Across all these cases, the message is clear. $G \times E$ interactions aren't just theoretical; they have real, tangible effects on how crops perform in the field. Ignoring them risks releasing varieties that flop the moment they leave the trial station. Instead, breeding programs need to pay attention to environmental variability, and maybe even redesign their trials to reflect the actual conditions farmers face. What these studies really show is the need for smarter, more grounded breeding; efforts that take regional differences seriously and avoid the trap of overly centralized decision-making. If the goal is to support Nigerian farmers with cultivars that work in the real world, then $G \times E$ data must move from the background to the foreground of breeding strategy.

Table 3: Summary of Case Studies on $G \times E$ Interactions in Nigerian Horticultural Crops

Crop	No. of Genotypes Tested	Environmental Conditions	Key Findings	Implications for Breeding and Adaptation	References
Cowpea	42 elite lines	5 diverse agroecological zones (e.g., Ibadan, Bauchi)	Significant $G \times E$ interaction observed. Genotypes G21 & G25 showed wide adaptability; others were location-specific.	Encourages targeted variety deployment across zones; supports scalable seed system planning.	Popoopa <i>et al.</i> , 2024
Bambara Groundnut	Multiple landraces	Arid and semi-arid regions	Morphological traits highly influenced by environment. Stress-tolerant traits varied across zones.	Demonstrates potential for breeding programs to focus on drought resilience with regional specialization.	Olanrewaju <i>et al.</i> , 2021
Cassava	10 improved varieties	Low and optimum nitrogen levels in multiple sites	$G \times E$ interaction significant for fresh root yield; some varieties stable across all nitrogen regimes.	Highlights importance of nutrient-use efficiency in cultivar selection.	Maroya <i>et al.</i> , 2013

Okra	29 accessions	4 seasonal environments	G×E interaction affected seed yield; some genotypes-maintained stability across all locations.	Suggests suitable candidates for year-round cultivation in varying seasonal conditions.	Nwangbunka <i>et al.</i> , 2011
Cucumber	6 genotypes	4 environments in Cross River State	High variability in yield performance across sites; GGE biplot revealed genotypes with wide adaptation.	Advocates for environment-specific recommendation frameworks in extension strategies.	Iwo & Odor, 2018

The table systematically captures the breadth of research conducted in recent years on how different Nigerian environments affect the performance of various horticultural crops. The first column identifies the crop species, each representing a vital horticultural product either for food security, income generation, or dietary diversification.

Technology on the Rise

Genomics and Gene Editing

Genomics entails the study of a complete set of genes in an organism. Gene editing involves adjustment, modification or making changes to genes domiciled in an organism. Gene editing could be carried out using conventional biotechnological methods or genetic engineering process. Genetic engineering, also called recombinant DNA technology, involves the alteration of genetic material to enhance or suppress the function of a gene or set of genes (Rawat *et al.*, 2024; Lu & Zhu, 2017; Jaganathan, 2018). Contrary to conventional biotechnological methods that may involve the combination of both desirable and undesirable genes, recombinant DNA technology selectively incorporates only desirable genes, thereby increasing the probability of developing abiotic and biotic stress-resistant varieties as well as high yielding species (Qin *et al.*, 2007).

Yi *et al.*, (2023) studied Growth-Regulating Factor (GRF) gene family in pineapple. The study identified eight GRF transcription factor genes and named them: AcGRF1 to AcGRF8 based on their chromosome locations. All AcGRF had a negative hydrophilic score, indicating that they are hydrophilic proteins. Subcellular localization predictions indicated that seven AcGRF proteins were localized to the nucleus and AcGRF 4 was localized to the membrane. The eight GRF were phylogenetically classified into five subfamilies. The chromosomal locations, phylogenetic relationships and expression profiles at different developmental levels were analyzed. The analysis included roots, stems, pistils, discs, peduncles, ovules, ovaries, fruit hearts, bracts, sepals and placenta. Collinearity analysis showed that early segmental duplications promoted expansion of the pineapple GRF gene family and purifying selection was the main force acting on the GRF genes. It was generally observed that GRF genes from the same clade tended to exhibit similar expression patterns. The roles

of GRF in floral organ development and response to gibberellin were revealed as well as their influence on pineapple's growth, development and stress responses. The findings could activate further research on the regulatory mechanisms of GRF transcription factors during pineapple growth and development.

Rawat *et al.*, (2024) reviewed biotechnology approaches and methods aimed at gene editing in horticultural crops. Biotechnological techniques such as Clustered Regularly Interspaced Short Palindromic Repeats (CRISPR) molecular markers and cryopreservation were critically reviewed to facilitate understanding towards improvement and productivity of horticultural crops.

CRISPR

CRISPR structure is based on the binding of ribonucleic acid (RNA) with deoxyribonucleic acid (DNA) to establish gene sequence specificity. The CRISPR method has been used to cause gene mutations in several vegetable crops, including cabbage, pineapple, tomato, and watermelon (Priyanka *et al.*, 2007; Qin *et al.*, 2007; Lu & Zhu, 2017; Jaganathan, 2018; Tang *et al.*, 2018; Kwon *et al.*, 2020). Genetic engineering offers a platform for the introduction of abiotic and biotic stress resistant genes domiciled in many wild strains of horticultural crops into cultivated varieties (Lu & Zhu, 2017; Jaganathan, 2018; Tang *et al.*, 2018). In Nigeria, genetically modified (GM) food crop, the Pod-Borer Resistant (PBR) Cowpea was released for commercial use in 2019. The transgenic cowpea emphasized its resistance to destructive pod borers, a menace that typically destroys 80 per cent of cowpea crops. Another GM food crop TELA Maize is drought-tolerant and resistant to fall armyworms, offering farmers the opportunity to optimize yields and profits (Isaac, 2024). CRISPR-associated 9 (CRISPR/Cas9) has emerged as the most widely utilized gene-editing tool over the past decade. It is renowned for its high efficiency, simplicity, and user-friendliness. The CRISPR/Cas system's principle is derived from the adaptive immune mechanism of type II prokaryotic organisms. The CRISPR/Cas systems can be categorized into three distinct types (I, II, and III), each employing unique molecular mechanisms to identify and cleave nucleic acid sequences. The protospacer adjacent motif (PAM) sequences, which are brief sequence motifs located next to the crRNA-targeted region on the invading DNA, are crucial in type I and type II systems, particularly during the phases of adaptation and interference. In horticultural crops, CRISPR Cas9 can use to improve the quality of produce by improving taste, aroma, shelf life of produce. It can also be used to modifying the architecture of fruit trees, ornamental flowers, and trees; enhancing yield potential; and bolstering resistance to pests, diseases, and environmental stress in plants (Rawat *et al.*, 2024).

Priyanka *et al.*, (2007) reviewed in-depth analysis of CRISPR-Cas9 applications in horticultural crop improvement. Special emphasis was placed on its role in enhancing plant immunity, increasing abiotic stress resilience, and improving post-harvest characteristics.

Table 4: Directions in CRISPS-Cas g for horticulture crops

Focus Area	Description	Expected Impact	Reference
Epigenome editing	Targeting gene expression without DNA modification	Higher acceptable regulatory framework	Qin <i>et al.</i> , 2007
Precision genome editing	Improving target specificity to reduce off target effects	Higher accuracy in genetic modifications	Lu & Zhu, 2017
Genome-edited hybrids	Developing crops with enhanced stress tolerance and yield	Increased productivity	Jaganathan <i>et al.</i> , 2018
CRISPR-Cas variants	New Cas enzymes with higher efficiency	Broader range of editable crops	Tang <i>et al.</i> , 2018
Multiplex genome editing	Editing multiple genes simultaneously	Faster trait development	Kwon <i>et al.</i> , 2020
CRISPR-Cas variants	Developing crops with enhanced nutritional profile	Broader range of editable crops	Priyanka <i>et al.</i> , 2007

CRISPR-Cas9 has emerged as a revolutionary tool for horticultural crop improvement, offering precise and efficient genome modifications to address key agricultural challenges. By enabling targeted edits, CRISPR facilitates the development of crops with enhanced disease resistance, improved stress tolerance, superior fruit quality, and enriched nutritional content. These advancements not only contribute to higher yields and reduced dependence on chemical inputs but also align with the goals of sustainable and climate-resilient agriculture (Isaac, 2024; Priyanka *et al.*, 2007).

Some horticulture crops have complex genomes or strong cell wall thereby obstructing effective delivery of genome-editing components via CRISPR-Cas. Public perception and consumer acceptance are also critical factors influencing the future of CRISPR-edited horticultural crops. Conventional methods such as *Agrobacterium*-mediated transformation and particle bombardment are also limited in terms of efficiency and tissue specificity (Priyanka *et al.*, 2007). Safdar & Safdar, (2024) opined those emerging techniques such as nanoparticle-based delivery and ribonucleoprotein (RNP) approaches, offer promising alternatives but require further optimization for large-scale application.

CRISPR/Cas9 are obviously becoming an essential tool in plant breeding (Yasrab *et al.*, 2019). The work presented in (Zhu *et al.*, 2020) targeted the cabbage CENH3 gene linked to haploid induction to optimize the conditions for PEG-mediated protoplast transformation to improve editing efficiency using CRISPR/Cas9 in a non-model horticultural plant. To effectively transfer the CRISPR/Cas9 vector into cabbage protoplasts, important parameters influencing transformation effectiveness, including PEG4000 concentration, incubation duration, and plasmid quantity, were assessed. Genome editing of cabbage was successful. The process could be adapted for genome editing of other horticultural crops as

well as deployed in studies involving transitory transformation techniques in protoplasts such as subcellular localization and gene function investigation.

Molecular Markers

Rawat *et al.*, (2024) asserted that molecular markers can be widely used in horticultural crops for assessing genetic diversity, selecting disease resistance, evaluating the quality of planting material, choosing rootstock, assessing genetic components and facilitating marker-assisted breeding. Molecular tools for marker-assisted breeding (MAB) offer the potential to tackle challenges that have been difficult to address with traditional methods, as well as enhance the efficiency of routine breeding processes. However, MAB will be most effective when it is seamlessly integrated into the various components of breeding programs, serving as an integral part of the overall strategy rather than being treated as a supplementary technique. They can be successfully applied to detect alterations at molecular level. Ibitoye & Akin-Idowu, (2017) studied the effect of molecular markers in horticultural crop breeding program. Marker-assisted selection (MAS) has gained considerable importance by improving the efficiency of plant breeding through precise transfer of genomic regions of interest (foreground selection) and accelerate the recovery of the recurrent parent genome (background selection). MAS have been widely used for simple inherited traits than for polygenic traits, although there are few success stories in improving quantitative traits through MAS. They are being used to monitor DNA sequence variation in and among the species and create new sources of genetic variation by introducing new and favourable traits from landraces, wild relatives and related species and to fasten the time taken in conventional breeding, germplasm characterization, genetic mapping, gene tagging and gene introgression from exotic and wild species. The success of MAS depends on many critical factors such as the number of target genes to be transferred, the distance between the target gene and the flanking markers, number of genotypes selected in each breeding generation, the nature of germplasm and the technical options available at the marker level. Karakaş (2024) supported the need to incorporate molecular markers into horticulture breeding programs to rapidly develop plant varieties with desirable characteristics to meet the increasing food demand of the rapidly growing world population.

Cryopreservation

Cryopreservation is an excellent technique used for the conservation of germplasm. It involves use of liquid nitrogen to maintain tissue at ultra-low temperature (-196 °C), making it a long-term preservation technique. Here, liquid nitrogen arrests all the metabolic and biochemical activities of plant tissue which makes it a long-term storage technique. However, preserving plants using cryopreservation is not easy, as most plants cannot tolerate the low-temperature stress. For this purpose, cryoprotectants are used to avoid extracellular and intracellular ice formation. The main purpose of cryoprotectants is to dehydrate the plant material to avoid crystallization of water (Rawat *et al.*, 2024). Dumet *et*

al., (2013) demonstrated the deployment of Cryopreservation for conservation of yam and cassava resources in Nigeria. Cryopreservation via droplet vitrification showed high efficiency for cassava meristems (79% average recovery) when these were excised from in vitro seedlings. The efficiency of the process dropped considerably (to >23%) when meristems were excised from field-grown plants, thus precluding the use of such explants for routine cryobanking. In yam, large disparities were observed in the ability of meristems to produce a shoot after cryopreservation ranging from 0 to 60%, depending on the accession. Overall, better recovery was observed for *Dioscorea rotundata* than for *D. alata*, the two main species tested. The work concluded that processing 100 meristems per accession and retrieving 30 to estimate the recovery rate of the batch were a good compromise for the cryobanking routine.

Drones, Imaging, and Smart Sensors

In recent times, Drones equipped with imaging and smart sensors have been increasingly used in horticulture thereby transforming practices such as crop monitoring, precision spraying, and irrigation management as depicted in Figure 1. This technology allows for early detection of pests and diseases, optimization of resource use, and improved overall crop health, leading to increased yields and reduced losses (Karakas, 2024). Drones furnished with high-resolution cameras. can capture detailed images of crops, allowing farmers to detect early signs of pest infestations, diseases, or water stress. Thereby ensuring the health status of crops. Drones are also used for precision spraying of pesticides and fertilizers. By targeting specific areas of the field that need attention, farmers can reduce the amount of chemicals used, making farming more environmentally friendly. This technique saves time and resources while reducing the environmental impact of traditional farming methods. Drones with multispectral cameras capture detailed crop images, enabling early detection of issues like pest infestations, disease, and nutrient deficiencies. Sensors provide real-time data on soil moisture, nutrient levels, and environmental conditions, allowing for optimized irrigation and fertilization practices. Smart imaging tools, including thermal and hyperspectral imaging, further enhance crop health assessment and early detection of stress factors (Alhassan, 2022).



Fig. 2. Drone for Precision Spraying. **Source:** Alhassan, 2022

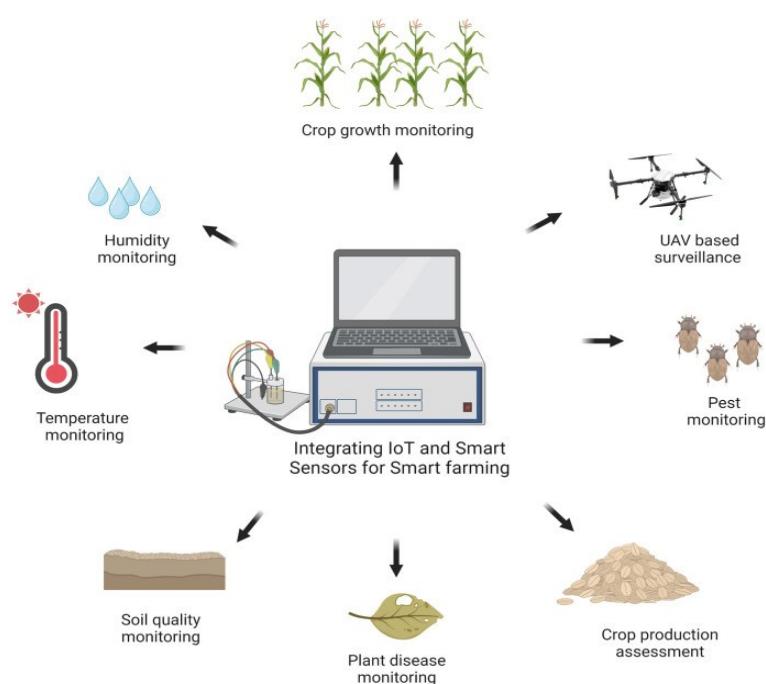


Fig. 3. Integrating Sensors for Smart Farming. **Source:** Rajak *et al.*, 2023

Studies in (Rajat *et al.*, 2023; Navarro *et al.*, 2023) have satisfactorily demonstrated the implication of integrated IoT-smart sensors in monitoring environmental factors such as moisture, humidity, temperature, and soil composition that are critical for crop growth. Greenhouse gases such as Carbon dioxide, Methane, are also measured through automated sensors. Smart farming also enables measurement of nitrogen contents in soil that helps farmers to determine the amount of fertilizers to be used in farm lands. Some IoT-enabled equipment and unmanned aerial vehicles are useful in accurate surveillance of pest attack and associated diseases in farm vegetation. Though the smart farming has great scopes in

future, it faces certain limitations related to high implementation cost, data security, and lack of sufficient digital knowledge in farmers. Special economic policies, data encryption, and digital literacy could ease IoT-enabled smart farming in future.

Artificial Intelligence in the Field

Amuda and Rahman, (2025) explored artificial intelligence (AI) for food production among small holder farmers in Nigeria with a view to achieve sustainable development goals (SDGs) in the Country. Content analysis and systematic literature review methods were used for the investigation. Findings of the study demonstrated that the application of AI can contribute to realization of operation: “zero hunger”. It was shown that AI can be used for weeding, spraying and harvesting. It was noted also that digitization of agriculture through AI tools reduces middlemen, expands market opportunities and enhances productivity.

Farooq *et al.*, (2024) posits that Artificial Intelligence (AI) has been used for various purposes, including optimizing crop management practices, detecting pests and diseases, and improving resource allocation. AI-powered systems can analyze data from sensors and weather forecasts to provide real-time information on soil conditions, weather patterns, and crop needs, helping farmers make informed decisions about planting, irrigation, and fertilization. AI can also be used to optimize irrigation systems and reduce water waste. Machine learning models can enhance plant breeding by predicting crop traits, identifying stress-resistant individuals, and optimizing breeding strategies (Farooq *et al.*, 2024). These models analyze vast datasets, including genetic information and phenotypic data, to identify patterns and correlations that might be missed by traditional breeding methods (Schridder & Kern, 2018). This enables breeders to make more informed decisions about which plants to select for breeding, ultimately leading to improved crop varieties with better yield, disease resistance, and stress tolerance.

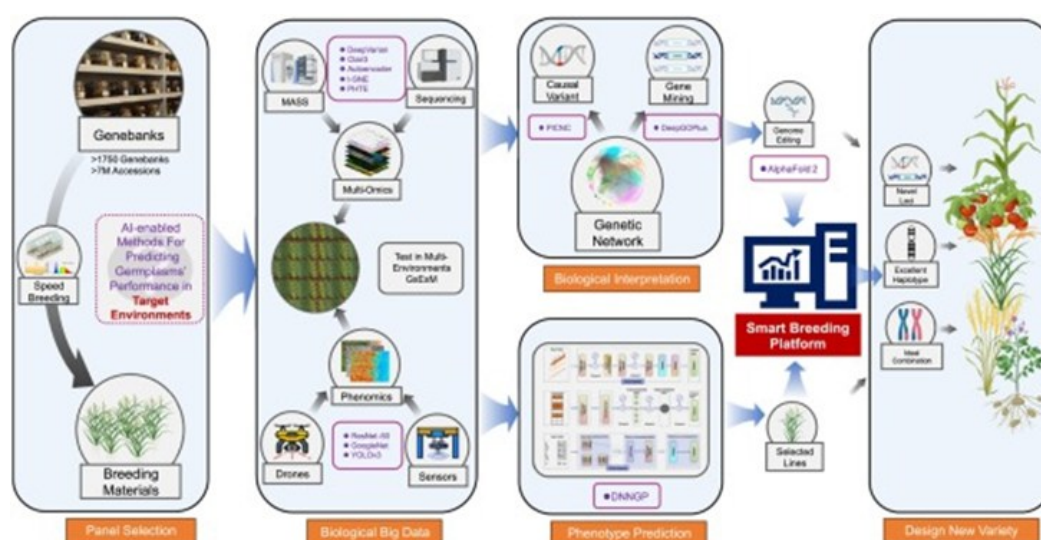


Fig. 4. A roadmap of AI-enabled plant breeding. Source: Farooq *et al.*, 2024

The source of germplasm is depicted in the far left. It is either used directly or subjected to breeding to utilize omic analyses to generate big data as presented in the second panel. The works in (Gao *et al.*, 2020; Farooq *et al.*, 2024; Schrider & Kern, 2018) agreed that big data from the germplasm could uncover genes and predict breeding values as shown in the third panel, which would characterize the gene-editing targets and optimal lines for developing next-generation cultivars as presented in the fourth panel.

Implications for Breeding and Improvement

Faster, Smarter Breeding

Automation in data collection and analysis has significantly accelerated genetic gains in plant breeding and genetic research. This rapid data acquisition allows researchers to make more informed selections and decisions in breeding programs, shortening the breeding cycle and increasing the pace of desirable traits being incorporated into new plant varieties (Sun *et al.*, 2024; Adjah *et al.*, 2022).

High-throughput phenotyping (HTP) using UAVs and drones to collect detailed data on plant health, stress levels and nutrient content is revolutionizing modern breeding programs (Sheikh *et al.*, 2024). UAV data can be used for disease and pest surveillance, assessing environmental stress, identifying nutrient deficiencies, aiding in the selection of resistant varieties and improving nutrient use efficiency (Telikani *et al.*, 2024).

Sun *et al.*, (2024) critically reviewed modern planting techniques in crop improvement and genetic diversity. The work asserted that the process of modern breeding starts from the creation of material populations, which can be constructed by natural mutagenesis, chemical mutagenesis, physical mutagenesis transfer of DNA(T-DNA), endogenous retrotransposon (Tos17). Then mining of gene function via Quantitative trait loci (QTL) mapping, bulked-segregant analysis (BSA), Genome-wide association studies (GWASs), RNA interference (RNAi) and gene editing. Massive amounts of data have been produced in recent decades as a result of the quick development of high throughput technology. The integration of AI technologies has enabled breeders to make informed decisions, reducing the time and resources needed to produce new plants varieties and improving the success rate of breeding programs.

Building Crops That Can Withstand Change

Menki *et al.*, (2024) developed drought-tolerant maize varieties to attain high yield. Breeders shifted from a wide area testing approach to the use of managed screening sites aimed at precisely controlling the intensity and timing of drought stress for developing drought-tolerant maize varieties. These sites coupled with the use of molecular markers allowed choosing suitable donors with drought-adaptive alleles for integration into existing elite maize lines to generate new drought-tolerant inbred lines. Genetic gains estimates were made using performance data of drought-tolerant maize hybrids evaluated in regional trials for 11 years under managed drought-stress, well-watered conditions, and across diverse rainfed environments. Results showed significant annual yield gains of 32.72 kg ha⁻¹

¹ under managed drought-stress, 38.29 kg ha⁻¹ under well-watered conditions and 66.57 kg ha⁻¹ across multiple rainfed field environments. The significant genetic relationship observed in the three growing conditions signaled the need to exploit the available genetic resources and modern tools in enhancing the development of drought-tolerant varieties.

Yahaya *et al.*, (2022) presented the opportunities and constraints of Sorghum production in Nigeria. 250 farmers were involved in a participatory rural appraisal (PRA) study conducted in three selected sorghum growing zones in northern Nigeria. Socio-economic data were collected through surveys and focus group discussions. Sorghum was cultivated mainly by males (80%) who had grade 6-12 level of education (31.3%), with the productive age of 21-45 years (75.7%) and a household family size of below five members (52.3%). Low yielding landrace varieties such as Kaura (37.4%) and Fara-fara (29.3%) were the most widely cultivated types across the study zones due to their good grain quality. Majority of the farmers preferred traits from Sorghum variety with high yield and drought tolerance. The study recommended integrated sorghum technology development that incorporates the aforementioned preferences of farmers for gainful production.

Badu-Apraku *et al.*, (2023) presented a study which sought to develop and deploy multiple stress-tolerant hybrids and open-pollinated Maize varieties. The most reliable secondary traits for selecting varieties for improved grain yield under drought-stress (DS), heat-stress (HS) and combined drought and heat stress (CDHS) were anthesis-silking interval, ears per plant and plant and ear aspects. Several early and extra landraces were identified as potential sources of tolerance to DS, HS and CDHS. Several qualitative trait loci (QTLs) associated with grain yield and key secondary traits were identified via genome-wide association studies in landraces and inbred lined lines. The study deployed conventional genetic breeding techniques to obtain a 26% and 49% increase in yield compared to commercial hybrid checks under CDHS and DS. The identified desirable qualities could be validated and integrated in genomic-enabled breeding for grain yield improvement of DS, HS and CDHS Maize varieties.

The simultaneous adopted decisions of drought-tolerant maize varieties and other climate-smart agricultural practices such as intercropping, row-planting, and inorganic fertilizer. Manure and residue incorporation was studied in Badu-Apraku *et al.*, (2023). The work used a nationally representative survey data from 1370 rural households in Nigeria. Multivariate Tobit and ordered Probit models were applied to assess the complementarity and substitutability effect among climate-smart agricultural practices (CSAPs) the predictors of the joint adoption and the adoption intensity of CSAPs. The result showed a significant positive correlation between drought-tolerant maize varieties (DTMVs) and inorganic fertilizer, the DTMVs and intercropping and DTMVs and manure. The strongest correlation was observed between DTMVs and manure.

Adjah *et al.*, (2022) discussed 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 could be achieved by developing drought-tolerant varieties through several

processes encompassing profiling of known QTLs and identification of new ones. A comprehensive strategy for breeding drought-tolerant rice varieties and other horticulture crops in Nigeria and West Africa is suggested.

Conclusion

Nigeria's horticultural crops carry more than just agricultural value; they represent the resilience, knowledge, and adaptability of communities that have shaped them over generations. This review highlights the rich genetic diversity found in Nigerian horticultural crops which is a key factor in their resilience to climate-related stresses such as drought, pests, and low soil fertility. Indigenous landraces, shaped through generations of farmer selection, remain central to this diversity, offering valuable traits for crop improvement alongside emerging genomic technologies. However, this genetic wealth is increasingly at risk due to unregulated hybridization, fragmented research efforts, and limited investment in breeding. To address these challenges, integrated approaches are needed by combining farmer knowledge with advanced breeding tools, and adapting them to Nigeria's diverse agroecological and socio-economic conditions.

Policy and research priorities should include strengthening decentralized seed systems, expanding locally driven breeding programs, and ensuring that innovations are accessible to smallholder farmers. Future studies should emphasize multi-location trials, molecular characterization of underutilized crops, and the development of gene editing and AI-assisted breeding tailored to local needs.

Ultimately, the horticultural sector in Nigeria holds significant potential to enhance food security and climate resilience. Realizing this potential requires coordinated efforts to conserve genetic resources, invest in appropriate technologies, and support farmers as essential custodians of crop diversity.

CRedit Authorship Contribution Statement

S.C. Onuchukwu: conceptualization, formal analysis, visualization, software, writing - original draft, and writing - review & editing; **I.C. Nnorom:** conceptualization, supervision, methodology, validation, visualization; **S.S. Udoh:** formal analysis, visualization, software and writing - review & editing; and **J.O. Opara:** formal analysis, visualization, software and writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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