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Advancing Resilient Legume Crops for Sustainable Agriculture and Feeding Africa: Genetics and Genomics Studies on Cowpea and Common Bean

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ABSTRACT

Legumes play a pivotal role in sustainable agriculture and global food security due to their ability to fix atmospheric nitrogen, enrich soil fertility, and provide protein-rich dietary staple foods. Among legumes, cowpea (Vigna unguiculata L.) and common bean (Phaseolus vulgaris L.) stand out as crucial crops, particularly in regions with resource constraints and climatic variability. Besides, cowpea and common bean play indispensable roles in Africa's agricultural food and nutrition security. This review delves into recent advances in genetic and genomic research aimed at fortifying the resilience of cowpea and common bean crops, essential for a sustainable agriculture and environment. In the context of cowpea, research efforts have concentrated on unraveling the genetic determinants of traits crucial for adapting to different agroecological conditions. Traits such as drought and heat tolerance, resistance to pests and diseases prevalent in farming systems, and improved biological nitrogen fixation capacity have been primary targets. Leveraging advancements in genomic tools currently including reference genomes and high-throughput sequencing, some researchers have identified candidate genes and molecular markers pivotal for biotic and abiotic stress resilience. Genetic and genomic studies on cowpea and common bean have underscored the importance of enhancing resilience to abiotic stresses and combatting prevalent diseases such as anthracnose, angular leaf spot and ashy leaf spot in bean production systems. Through the identification of quantitative trait loci (QTLs) and candidate genes associated with stress tolerance and nutritional quality, genomic-assisted breeding approaches hold promise for developing bean varieties tailored to African agroecosystems. Overall, integration of genetics and genomics in cowpea and common bean research offers a transformative pathway towards developing resilient legume crops tailored to different needs and agroecologies. These advancements are poised to bolster agricultural sustainability, enhance food security, and contribute to improved livelihoods across the globe.

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RÉSUMÉ

Les légumineuses jouent un rôle crucial dans l'agriculture durable et la sécurité alimentaire mondiale en raison de leur capacité à fixer l'azote atmosphérique, à enrichir la fertilité des sols et à fournir des aliments de base riches en protéines. Parmi les légumineuses, le niébé (Vigna unguiculata L.) et le haricot commun (Phaseolus vulgaris L.) se distinguent comme des cultures essentielles, en particulier dans les régions aux ressources limitées et à la variabilité climatique. De plus, le niébé et le haricot commun jouent des rôles indispensables dans la sécurité alimentaire et nutritionnelle du continent. Cette revue explore les avancées récentes en matière de recherche génétique et génomique visant à renforcer la résilience des cultures de niébé et de haricot commun, essentielles pour une agriculture et un environnement durables. Dans le contexte du niébé, les efforts de recherche se sont concentrés sur la compréhension des déterminants génétiques des traits cruciaux pour l'adaptation à différentes conditions agroécologiques. Les traits tels que la tolérance à la sécheresse et à la chaleur, la résistance aux ravageurs et aux maladies courantes dans les systèmes agricoles, et l'amélioration de la capacité de fixation biologique de l'azote ont été les principales cibles. En tirant parti des avancées des outils génomiques incluant actuellement les génomes de référence et le séquençage à haut débit, certains chercheurs ont identifié des gènes candidats et des marqueurs moléculaires essentiels pour la résilience aux stress biotiques et abiotiques. Les études génétiques et génomiques sur le niébé et le haricot commun ont souligné l'importance de renforcer la résilience aux stress abiotiques et de combattre les maladies courantes telles que l'anthracnose, la tache angulaire des feuilles et la tache cendrée des feuilles dans les systèmes de production de haricots. Grâce à l'identification de loci de caractères quantitatifs (QTL) et de gènes candidats associés à la tolérance au stress et à la qualité nutritionnelle, les approches de sélection assistée par la génomique promettent de développer des variétés de haricots adaptées aux agroécosystèmes africains. Dans l'ensemble, l'intégration de la génétique et de la génomique dans la recherche sur le niébé et le haricot commun offre une voie transformative pour développer des cultures légumineuses résilientes adaptées à différents besoins et agroécologies. Ces avancées sont prêtes à renforcer la durabilité agricole, à améliorer la sécurité alimentaire et à contribuer à l'amélioration des moyens de subsistance à travers le monde.

Mots-clés: amélioration des cultures, génomique, légumineuses, fixation de l'azote, Phaseolus vulgaris L., loci de caractères quantitatifs, Vigna unguiculata L.

Introduction

Globally climate change has had significant negative impacts on natural ecosystems and biodiversity, largely driven by depletion of crop diversity, fluctuating weather conditions, and gradual depletion of soil fertility due to various multifactorial stresses (Rivero *et al*., 2022). Concurrently, the world population is increasing exponentially, while crop yields are declining, the emergence of new pathogen and pest variants are on the rise (Diouf, 2011), and natural resources are being depleted, posing a serious threat to human survival.

The agriculture sector plays a critical role in ensuring food security, promoting sustainable economic development and enhancing the quality life of human-kind (Pawlak and Kołodziejczak, 2020). By 2050, the global population is estimated to increase to 9.7 billion from the current over 8 billion. This demographic surge necessitates a 70% to 100% increase in food production, which can be achieved through the enhancement of major food crop yields, development of protein rich and climate resilient crop varieties (FAO, 2020; Simkin *et al*., 2019).

Despite the fundamental need for food, current production levels are insufficient to feed the global population, largely due to the interplay of anthropogenic and natural stresses that disturb the ecosystems. Delabre *et al*. (2021) highlighted that current food production and consumption trends are misaligned with the Convention on Biological Diversity's 2050 vision of living in harmony with nature. In response, agricultural scientists including breeders, pathologists, agronomists, and biotechnologists are leveraging advanced and innovative agricultural technologies to develop and deploy high yielding, nutrient-dense and climate resilient crops (Diouf, 2011; Sehgal *et al*., 2017; Jimenez-Lopez *et al*., 2023; Cohen *et al*., 2021).

FAO (2023) reported that about 33 African countries need assistance in terms of food supply, majority of them found in sub-Saharan Africa (SSA). The persisting drought in East Africa raises serious concerns about levels of acute food insecurity in the region and Africa at large. Notably, the food security of sub-Saharan Africa is dependent on a few major crops, providing largely only an energy source in the diet. To address this, crop diversification and climate -resilient crops with wide adaptation to climate change is imperative, thus warranting focus on promoting cultivation of African neglected or underutilized crops. Culturally, these crops are linked with the food habits of the communities and they are nutritionally rich, have untapped genetic diversity, and adaptation to harsh climate conditions and marginal soils (Abberton *et al*., 2022).

Grain legumes are among the most critical agricultural crops for achieving food and nutrition security in smallholder farming systems in SSA. These crops are considered climate resilient and environmentally sustainable crops (Vanlauwe *et al*., 2019). Similarly, Lisciani *et al*. (2024) indicated that legumes are a cost-effective source of nutrients for low-income countries and provide a sustainable and healthier protein option compared to animal-based proteins in developed countries. Legumes are rich in proteins and various minerals, and they have the ability to fix atmospheric nitrogen, which conserves the soil biotypes, later enhances soil fertility and environmental sustainability (Horn *et al*., 2022; Guo *et al*., 2023). For instance, legumes such as soybean, cowpea, common bean, chickpea, faba bean, garden pea and clover are major protein sources for humans and livestock (Boukar *et al*., 2019). In contrast, cereal crops like maize, sorghum, millet, wheat, and rice are the primary carbohydrates sources. The development of high-yield cereal crops typically necessitates the application of chemical nitrogen (N_2) fertilizers. However, legumes form symbiotic root nodules with rhizobia bacteria, facilitating Biological Nitrogen Fixation (BNF), which provides the nitrogen needed for their growth and development (Guo *et al*., 2023). This BNF process is the primary reason legumes are protein-rich compared to all other plants (Broughton *et al*., 2003), through their nitrogen-fixing qualities (Breen *et al*., 2024).

Indeed, BNF is a vital agriculture and environment process enabling legumes to convert atmospheric nitrogen into plant-usable form, thereby promoting soil fertility (Bado *et al*., 2006). This natural process reduces the reliance on synthetic nitrogen fertilizers, decreasing environmental pollution and enhancing agricultural sustainability. Hence, legumes are integral to Climate Smart Agriculture and Sustainable Intensification concepts aimed at sustainable crop production and improved resilience to climate change and variability (Lipper *et al*., 2014; Munjonji *et al*., 2018; Vanlauwe *et al*., 2019; Dutta *et al*., 2022).

Several studies have demonstrated the importance of BNF in sustainable agriculture. The BNF provides many functional benefits for agroecosystems (Ladha *et al*., 2022). Unkovich *et al*. (2008) showed that legume crops could fix up to 200 kg of nitrogen per hectare per year. This indicates their potential for reducing the need for synthetic fertilizers. Another report by Ladha *et al*. (2022) emphasized the role of BNF in improving soil fertility and enhancing crop yields, by replenishing the reservoirs of soil organic N and improving the availability of soil N to support crop growth. Therefore, rhizobium-legume symbioses have a major contribution to natural or biological N_2 fixation.

Cowpea and common bean are vital protein sources for impoverished communities in sub-Saharan Africa's small scale farming systems. These legumes play a crucial role in sustainable agriculture and environmental protection by fixing atmospheric nitrogen through symbiotic relationships with rhizobia, thereby reducing the need for synthetic nitrogen fertilizers, which can harm the environmental sustainability. Advances in genetics and genomics now enable researchers to explore genomic resources to identify and manipulate genes responsible for BNF in legume crops (Diouf, 2011; Munjonji *et al*., 2018; Seido *et al*., 2019; Jimenez-Lopez *et al*., 2020). By studying the genomes of cowpea and common bean, breeders can identify key genetic markers associated with nitrogen fixation and breed for traits that enhance this ability.

Using genomic resources and breeding techniques, researchers can also develop resilient cowpea and common bean varieties that are better adapted to various environmental conditions such as abiotic stress tolerance in common bean (Peer *et al*., 2023), drought tolerance (Cui *et al*., 2020), heat stress (Boukar *et al*., 2018; Jha *et al*., 2020; Mohammed *et al*., 2024) and salinity tolerance (Amorim *et al*., 2018; Ravelombola *et al*., 2022) in cowpea. Even though cowpea is a drought tolerant legume, different genotypes respond differently to drought, resulting in up to 100% or more yield increases in the case of resistant genotypes or 50% or more yield loss in case of susceptible types (Yahaya *et al*., 2019). These resilient varieties can boost yields, and reduce agriculture's environmental footprint by decreasing the need for chemical fertilizers. By harnessing the power of genetics and genomics, we can create more sustainable and resilient legume varieties that contribute to food security and environmental sustainability in Africa.

LegumesasAgriculturaland Environmental Resilient Enhancers. The food gap in the world creates unstable existence and development of insufficient humanity infrastructures (Kopteva *et al*., 2018). Conversely, feeding the future humanity's will at risk, need increasing pressure upon used natural resources, provoke inequality growing due to climate change effects. However, there are opportunity resilient crops to sustain the future humanity needs. Legumes play a crucial role in enhancing agricultural and environmental resilience, especially in low-inputs or organic agriculture systems (Stagnari *et al*., 2017; Vanlauwe *et al*., 2019). The future research should investigate local legume varieties and rhizobia interactions. Identifying locally adapted rhizobia strains may inform future management practices to build natural nitrogen-fixing capabilities in underutilized legumes (Abberton *et al*., 2022). Zhao *et al*. (2022) highlighted that legume-based rotations are critical for improving global crop production, particularly when integrated into low-input and low-diversity agricultural systems. Likewise, legumes significantly contribute to Integrated Soil Fertility Management (ISFM) due to their ability to fix atmospheric nitrogen (N_2) in symbiosis with rhizobia, supplying organic resources and enhancing fertilizer uptake and suppressing weeds among other benefits (Harrison *et al*., 2006; Dakora *et al*., 2015; Mogale *et al*., 2023).

The level of N_2 fixation varies among legumes depending on the critical temperature for N_2 fixation, edaphic and environmental factors. For instance, the critical temperature for cowpea ranges between 35 and 40°C (Rainbird *et al*., 1983), whereas for optimum nodule functioning in common beans (*Phaseolus* spp.) ranges from 25 to 30°C and but it can hinder by root temperatures between 30 and 33°C (Piha and Munns, 1987; Hernandez-Armenta *et al*., 1989). Since the availability of synthetic nitrogen fertilizer to smallholder farmers is limited by cost, distribution and lack of credit, incorporating legumes into farming systems can substantially improve soil fertility. This is why legumes are an integral component of Climate Smart Agriculture and Sustainable Intensification (CSASI) crops, that are aimed at sustainable crop production and improved resilience to climate change and variability (Lipper *et al*., 2014; Vanlauwe *et al*., 2019).

Cowpea is inherently resilient to drought and high temperatures (Hall, 2004). In the context of global climate change, cowpea is a reliable source of plant-based protein and folic acid, making it a valuable component of sustainable agriculture, especially in Africa (Liang *et al*., 2024). Currently, cowpea is listed under the drought tolerant and protein rich but underutilized legume crop in Africa (Morgan, 2023). It is indigenous to SSA, and has significant role for human and planetary health. It is worth noting that underutilized legumes contribute to agroecosystems and food security impressively in Africa. Similarly, common bean exemplifies in agricultural and environmental resilience, addressing the complexities of modern agriculture and environmental sustainability (Lisciani *et al*., 2024). As shown in Table 1, underutilized legumes such as cowpea and common bean have the potential in climate resilience and N fixation ability. Continued research and breeding efforts are essential for ensuring food security, mitigating climate change impacts, and fostering sustainable agricultural systems worldwide.

Agricultural and environmental resilient crops are vital for economic growth and improved livelihoods. Researchers have developed improved climate-resilient varieties in various crops, resistant to multiple stress factors, including abiotic and biotic stress such as both human-made and climate-driven, and soil-associated factors (Kole *et al*., 2015). Developed countries such as USA, Europe and China have adopted climate-smart agriculture initiative strategies to ensure food security. Modern agriculture, which currently encourages homogeneity, needs to diversify the species and cultivars of cultivated plants (Kopeć, 2024). However, the increased frequency and severity of extreme weather events have reduced the productivity of major food and feed crops, posing a significant threat to global and regional food security (Rivero *et al*., 2022).

Cowpea

Cowpea (*Vigna unguiculata* L.) is a diploid (2x = 2n = 22) legume species with a relatively small genome size of approximately to 620 Mbp (Boukar *et al*., 2018). It is grouped under the family of Fabaceae and sub-family Faboideae. Cowpea is a self-pollinated crop with narrow genetic diversity, making it susceptible to various environmental factors (Horn *et al*., 2022). It is originated and domesticated in East and West Africa, and then to Asia and new world (Herniter *et al*., 2020). Now it is cultivated in every continent except Antarctica. There are ten wild perennial subspecies and one annual subspecies of cowpea, with *Vigna unguiculata* ssp. *dekindtiana* var. *spontanea* considered as the progenitor of domesticated cowpea (Pasquet, 1996; Maxted *et al*., 2004; Pasquet *et al*., 2021). Cowpea is known by various common names including southern pea, black eye pea and crowder pea in United states, *luba hilu* in Sudan, *niebe* in Francophone region of Africa, *Seub* and *niao* in Senegal, *wake* or bean in Nigeria, *lobia* in India, *caupi* in Brazil, asparagus bean in China and coupe or frijole in Mexico (*Cowpea (Revised) | Infonet Biovision Home. (infonet-biovision.org;* Anon, 2016).

Nigeria is the largest producer and consumer of cowpea, accounting for 48% of production in Africa and 46% worldwide, with about 95% of global production in West Africa (IITA, 2024), with a total production of 3.6 million tons in 2021 (Nwagboso *et al*., 2024). Hence, the production of cowpea is dominated by sub-Saharan Africa, particularly in West Africa, which accounts for 60% of worldwide production (Nkomo *et al*., 2021). Predominantly cowpea production is practiced by smallholder farmers under marginal conditions, often intercrop with maize, sorghum, or millet. It is a common grain legume grown in arid and semiarid regions globally (Freitas *et al*., 2012). Primarily cowpea is grown for food, fodder, vegetable, green manure, and as a cover crop. Cowpea grains contain 20%-32% protein with high amounts of essential amino acids (lysine and tryptophan), minerals (zinc, iron, calcium), vitamins (thiamine, folic acid, and riboflavin) and fibers (6%) (Boukar *et al*., 2018). The nutritional content of cowpea is high as it was highlighted by Dakora (2013), with leaves containing 35-40% protein and the grain has about 34% and 57% protein and carbohydrates, respectively. That is why cowpea is considered as the "hungry-season crop", since it is the first crop to be harvested often 60-80 days after emergence, which is much earlier than when the cereal crops become ready for harvest. It also provides high quality legume hay for livestock feed (Gómez, 2004; Kamara *et al*., 2018).

The name “cowpea” by itself probably originates from when it was an important livestock feed for cows in the United States

In sub-Saharan Africa, cowpea is among the recognized African indigenous nutrient-rich vegetables with the potential to promote food and nutrition security (Owade, 2019). Similarly, in East Africa, cowpea acts as a source of vegetable and grain for human consumption, where it is widely grown in Kenya, Tanzania, South Sudan and Uganda (FAOSTAT, 2024). In Uganda, the yield of cultivated cowpea varieties ranges from 760 kg to 1600 kg/ha (Mbeyagala *et al*., 2021); which is below the yield potential of improved cowpea varieties under optimal management practices, estimated at 2.5 to 3 ton/ha (Kamara *et al*., 2018).

Cowpea is a key climate-resilient legume for food security in sub-Saharan Africa (Mohammed *et al*., 2024), often intercropped it normally with maize, millet, sorghum, and cassava. Its ability to fix more atmospheric nitrogen than soybean and common bean, makes it a valuable crop for reducing the need for synthetic fertilizer application (Bado *et al*., 2006; Nyemba and Dakora, 2010). In agricultural system, cowpea compensates for the nitrogen absorbed by cereals (Kebede and Bekeko, 2020). Due to its hairy nodules, cowpea can fix nitrogen well even in poor soils with over 85%

Table 1. General characteristics and production of cowpea and common bean in sub-Saharan Africa.

S. N	Categories	Cowpea (black eye pea/bean)	Common bean (haricot/field bean)
1	Center of origin/diversity	Sub-Saharan Africa	Central Asia Center (India, Pakistan, Afghanistan, south Russia), Middle East Center (Iran, Iraq), Mediterranean Center (Turkey, Greece, Lebanon), Africa (Ethiopia)
2	Maturity period (days)	60-80	65-200
3	Chromosome number	2n = 2x = 22	2n = 2x = 22
4	Genome size	620	450 - 650
5	N derived from fixation (%)	30 - 96	3 - 55
6	N contribution (kg ha⁻1)	8 -198	1-6
7	Grain yield (kg ha⁻1)	50 - 3500	394 -1589
8	Top producers in ascending order as of 2020	Nigeria, Niger, Burkina Faso, Tanzania, Myanmar	China, Ethiopia, Egypt, Australia
9	References	(Daryanto *et al*., 2015; Kamara *et al*., 2018; Herniter *et al*., 2020)	Dakora *et al*., 2015; Mukankusi *et al*., 2019; Nyemba and Dakora, 2010; Katungi *et al*., 2009

sand, less than 0.2% organic matter and low phosphorus levels (Kassa *et al*., 2012; Mulugeta *et al*., 2016). This trait positively impacts on soil structure and hence cowpea is often used in rotation systems to improve soil fertility in marginal areas (Kebede and Bekeko, 2020). Additionally, the biomass of cowpea haulm, remaining after harvest, serves as source of quality fodder for ruminant livestock, particularly in the Sahelian region of SSA (Boukar *et al*., 2016).

Common bean. Common bean (*Phaseolus vulgaris* L.) also known simply as bean, is a diploid legume crop (2n = 22) grouped under the family Fabaceae, with a genome size ranging from 450 to 650 Mbp; (Gepts, 2001; Rendón-Anaya *et al*., 2017; Flake *et al*., 2019). It is a self-pollinated legume crop, although a small degree of cross-pollination can occur via insects such as bees and flying insects (Katungi *et al*., 2009). Common bean is an annual grown crop, maturity period ranges from 65 to 110 days from emergence (Buruchara, 2007). However, the maturity period may extend up to 200 days after planting on some varieties of climber beans grown in cooler upland elevations (Graham, 1997). It is widely cultivated for its edible dry seed and/or immature seed pods; its leaf is also widely used as a vegetable and the straw as fodder for livestock. Based on ecogeographical and genetic diversity during domestication processes, common beans are classified into two gene pools: Mesoamerican gene pool and Andean gene pool (Bitocchi *et al*., 2012; Cichy *et al*., 2015) and the differences between the two are shown in Table 2.

Common bean is cultivated in over 120 countries, thriving under varying temperatures, light intensities, relative humidity, rainfall distributions and technological levels which contribute to its global production instability (Pereira *et al*., 2018; FAO, 2022). It is the second most economic and societal important leguminous food crop next to the soybean. Hence, it is the most significant food legume in India, the main producer of common bean followed by Brazil, Myanmar, China, United States of America and Mexico; and east and southern Africa in Tanzania, Uganda, Ethiopia and Kenya (FAOSTAT, 2024) (Table 1).

Table 2. Difference between Mesoamerican and Andean gene pool varieties of common bean based on ecogeographical and genetic diversities during domestication processes.

S.N	Type of Differential Traits	Mesoamerican Gene Pool	Andean Gene Pool
1	Genetic Diversity	Wider genetic base	Narrow genetic base
2	Growth Habit	Indeterminate (climbing type)	Determinate (bushy type)
3	Artificial Support	Required	Not required
4	Seed Size	Small	Large
5	Mostly Grown Areas	North and Central America	Africa, Europe, and South America
6	Genetic Improvement	Advanced	Lagged behind
7	Genome Size	549.6 Mbp (Vlasova *et al*., 2016)	587 Mbp (Schmutz *et al*., 2014)

It is often referred to as the "poor man's meat" due to its crucial role in the diet of underprivileged communities of the aforementioned countries (Dutta *et al*., 2022). In addition, Mukankusi *et al*. (2015) highlighted that common bean is consumed and traded by more than 100 million households, hence targeted for reducing hunger and poverty, and therefore vital to Africa's struggle in achieving the UNs' Sustainable Development Goals (SDGs). Likewise, Broughton *et al*. (2003) emphasized that solving world hunger necessitates safeguarding and improving the productivity of farmers in poor countries.

Dietary proteins are commonly derived from legumes, specifically plants of the bean and pea family (Beebe *et al*., 2001). In response to this, the international consortium, 'Phaseomics' was established to develop new common bean varieties tailored to the preferences and requirements of local farmers and consumers. In Eastern and Southern Africa, beans are the second most important source of dietary protein and the third most important source of calories (Broughton *et al*., 2003). Common bean's ability to thrive in diverse environmental conditions and its critical role in providing dietary protein underscore its importance in global food security efforts. Continued research and genetic improvement are essential for enhancing the resilience and productivity of common beans, thereby contributing to sustainable agricultural practices and improved livelihoods worldwide

The Abundance of Biotic Stresses in Legume Crops. Climate change in particular increases disease and insect pressures, reducing yields and quality of legume cultivars (Moss *et al*., 2020). According to Sharma *et al*. (2016), the production and productivity of grain legumes is constrained by several biotic and abiotic factors, and suffer an average of 31.9 to 69.6% loss in crop productivity due to insects, diseases, drought, weeds, and soil fertility. Currently, majority of legumes are significantly impacted by biotic stress, which negatively impacts their development, production and nutritional value (Sandhu *et al*., 2023). Leguminous crops yield losses of up to 100% can occur under high biotic stress conditions, particularly in Asia and Africa (Singh *et al*., 2022). The prevalence of biotic stresses in legume crops varies depending on geographical location, climate, cropping systems, and agronomic practices (Pande *et al*., n.d.). That is why some ecological regions may face a higher prevalence of certain biotic stresses compared to others. Overall, legume crops are particularly susceptible to a wide range of biotic stresses due to their cultivation in diverse agroecosystems.

Fungi diseases. Fungi diseases such as anthracnose, fusarium wilt, root rot, and powdery mildew are common in many legume-growing regions, especially in high humidity and warm climate conditions. These fungal pathogens can significantly impact legume crops, reducing yield and quality. For instance, white mold caused by *Sclerotinia sclerotiorum*, angular leaf spot caused by *Pseudocercospora griseola*, and web blight and root rot caused by *Rhizoctonia solani*, can cause production losses of up to 100% in common bean (Taboada *et al*., 2022). Anthracnose causes by *Colletotrichtim lindemuthianum*, Root rot or Damping-off diseases caused by *Rhizoctonia* sp., Fusarium wilt caused by *Fusarium oxysporum* f. sp. *tracheiphilum* (Fot), are some of the diseases that pose a major threat to cowpea production worldwide, usually causing the lower leaves on one side of the plant to turn yellow (Omoigui *et al*., 2018).

Bacterial diseases. Bacterial diseases including bacterial blight, bacterial wilt, and crown gall are of significant concerns in areas with high humidity and moisture conditions. Bacterial blight caused by *Xanihomonas campestris pv. Vignicola*, is the most widespread disease of cowpea, as it has been reported all regions of the world in which cowpea is cultivated (Emechebe and Florini, 1997). These bacterial infections can lead to severe crop losses if not managed properly.

Viral diseases. The viral disease such as Bean common mosaic virus (BCMV), Bean yellow mosaic virus (BYMV), and Alfalfa mosaic virus (AMV) are widespread across tropical and sub-tropical regions. These viruses affect legumes globally, leading to substantial yield reductions (Beatrice *et al*., 2017). In Africa alone these viral pathogens are estimated to cause up to 10% of the overall yield reduction in common bean, approximately 2,288,000 tons annually

(Gabrekiristos and Wondimu, 2022).

Nematodes. Nematode infestation, particularly root-knot nematodes and cyst nematodes are prevalent in soils where legumes are grown continuously or in rotation with other susceptible crops. Root-knot attacks many major food crops resulting in reduction in quality and quantity of food and feed. Several species of nematodes are known to cause losses to cowpea throughout the world. Based on occurrence and frequency of root-knot nematodes, a survey was held among cowpea grown regions of Nigeria (Olowe, 2004) and Burkina Faso (Sawadogo *et al*., 2009). Six (*Helicotylenchus, Meloidogyne*, *Pratylenchus*, *Scutellonema*, *Telotylenchus*, and *Tylenchorhynchus*) and three (*Meloidogyne incognita*, *M. javanica* and *M. arenaria*) root knot species were the most significant parasitic potential on cowpea, respectively. These nematodes cause significant damage to legume root systems, leading to reduced plant vigor and yield. Caveness and Ogunfowora (1985) listed 55 species of plant parasitic nematodes associated with cowpea production. The root-knot nematodes, *Meloidogyne incognita* and *M. javanica* are documented to cause major losses, with *M. incognita* indicated to be the most detrimental species to cowpea (Sarmah and Sinha, 1995).

Insect pests. Pre- and post-harvest insect pests in legumes cause significant losses in sub-Saharan Africa (Abdoulaye *et al*., 2016). The common insect pests in legume crops include Aphids, thrips, beetles, and caterpillar. Some pests are geographically restricted; for example, the bean fly is prevalent in Africa but absent in Latin America, while the bean pod weevil is economically important in Mexico and some Central American countries. Other pests such as bruchids and leafhoppers are widespread in tropical bean-producing regions (CIAT, 1989). The bruchid (*Callosobruchus maculatus* F.) is the most damaging storage pest causing up to 95% loss in cowpea yield under non-treated conditions (Kpoviessi *et al*., 2020), and is also responsible for 48-100% loss in seed quality and quantity of common bean (Osorno *et al*., 2024).

Weeds. Weed competition is another significant biotic stress for legume crops. The infestation of weeds varies widely depending on soil type, cropping intensity, and weed management practices. If not adequately controlled, weeds can significantly reduce legume yield and quality. For example, in Nigeria, not controlling weeds results in 50-60% losses in legumes (Ado, 2007, cited in Imoloame *et al*. (2021). Cowpea suffers from weeds particularly when the crop is at early growth stages. Cowpea yield losses can reach up to 76% depending on the cowpea cultivar, environment and weed management practices (Osipitan *et al*., 2017). Uncontrolled weed populations can also substantially reduce the yield of common beans, up to 70% (Mengesha *et al*., 2013).

Integrated pest management. The specific abundance of biotic stresses may differ from one location to another, making it crucial for farmers to be aware of potential threats. Implementing integrated pest management (IPM) strategies is essential to mitigate the impact of these biotic stresses on legume crops. IPM approaches include crop rotation, resistant varieties, biological control agents, and shrewd use of chemical pesticides. As it was reported by Togola *et al*. (2023), numerous IPM opportunities have been developed, tested and validated for combating cowpea insect problems in West Africa. Environmentally safer and scalable IPM innovations will provide cowpea stakeholders with perceptions into workable, sustainable solutions for minimizing crop pest problems, reducing reliance on harmful pesticides and ultimately ensuring the long-term viability of cowpea production and its contribution to food security use of resistant varieties, biological control agents, and judicious use of chemical pesticides.

Understanding and managing the various biotic stresses in legume crops is critical for maintaining crop health and productivity, ensuring food security, and supporting sustainable agricultural practices. Generally, while the specific abundance of biotic stresses may differ from one location to another, it's essential for farmers to be aware of potential threats and implement integrated pest management strategies to mitigate their impact on legume crops.

Breeding for Biotic Stress Resistance in Cowpea and Common Bean. Cowpea and common bean face numerous agronomical challenges that can affect their growth, yield, and overall productivity before and after harvesting. Effective management and breeding for resistance is therefore crucial for ensuring crop resilience and productivity.

Common diseases and pests in cowpeas. Cowpea is often cultivated in regions with erratic rainfall patterns or in arid and semi-arid areas where water availability is limited. Drought stress significantly reduces cowpea yields and affects plant growth and development (Thiombiano *et al*., 2023). Hence, the crop becomes susceptible to various pests and diseases, including aphids, pod borers, nematodes, anthracnose, powdery mildew, and bacterial blight (Horn *et al*., 2020). These pests and diseases can cause significant yield losses if not properly managed. Additionally, cowpea is vulnerable to post-harvest losses due to insect damage, mold growth, and improper storage conditions (Kpoviessi *et al*., 2020; Tazerouni *et al*., 2019). Adequate post-harvest handling and storage practices are crucial to minimize losses and maintain the quality of harvested cowpea grains.

Common diseases and pests in common bean. Common bean is affected by numerous diseases, which can significantly depreciate the quality of the product and decrease crop productivity due to its nature of broad edaphoclimatic adaptations (Marcon *et al*., 2020). The crop is vulnerable to diseases such as anthracnose, bean rust, Bean common mosaic virus, angular leaf spot, halo bacterial blight, Beet curly top virus, Bean golden yellow mosaic virus, common bacterial blight, root rots, white mold and bacterial blight (Miklas *et al*., 2006). Environmental conditions, pathogen prevalence and cultivar susceptibility, influence the disease pressure. Similar to cowpea, common bean faces challenges from insect pests such as aphids, bean weevils (bruchids), leafhoppers, thrips, whiteflies, and pod borers (Miklas *et al*., 2006). Therefore, researchers have been pushed to develop resistant common bean varieties using both classical breeding and marker assisted selection breeding tools.

Among the major fungal diseases affecting the aerial part of common bean**,** Anthracnose, caused by *Colletotrichum lindemuthianum,* is particularly notable. Depending on cultivar susceptibility, favorable environmental conditions and the presence of the initial inoculum, anthracnose can cause losses of up to 100% in susceptible cultivars, and depreciate the product due to grain staining (Gonçalves *et al*., 2023; Mohammed, 2013). Majority of Anthracnose species grew at temperatures ranging from 10°C to 35°C (Salotti and Rossi, 2022). They are more prevalent in areas with temperature ranges between 15 to 26°C, high relative humidity (RH ≥ 95 %) and frequent rainfall.

Advanced breeding tools have led to development of resistant common bean varieties to anthracnose such as the Andean bean cultivar *BRSMG Realce* (formerly called *Co-Realce*) (Gomes-Messias *et al*., 2022) and *Beija Flor* (Marcon *et al*., 2020). Additionally, Andean cultivars CAL 143, 277, and the Mesoamerican cultivar, *Ouro Negro* have shown resistance to angular leaf spot (Rodríguez *et al*., 2019).

Gomes-Messias *et al*. (2022) highlighted that anthracnose resistance in the *BRSMG Realce* cultivar is controlled by a single locus with complete dominance. Identifying the local and international resistance sources and integrating multiple resistance genes into preferred market classes is crucial for developing anthracnose-resistant common bean cultivars (Ghalmi *et al*., 2009).

Genetic resistance is an effective and environmentally friendly strategy for disease management. Rodríguez *et al*. (2019) highlighted the use of improved varieties combining resistance genes of Andean and Mesoamerican origin as an effective approach to control Angular Leaf Spot (ALS) disease. Similarly, Viteri *et al*. (2022) demonstrated that identifying resistant genes (QTL) and introgression them into susceptible common bean cultivars is effective for controlling Ashy stem blight (ASB). This strategy is superior to crop rotation and fungicide use, which are often inadequate for efficient disease control (Singh and Schwartz, 2010).

Overall, breeding for biotic stress resistance in cowpea and common bean involves the development and deployment of resistant arieties, which is a sustainable approach to managing diseases and pests while minimizing environmental impacts.

Genetics and Genomic research on Biotic stress resistant legume crops. Genetics and genomics play a crucial role in crop improvement, offering targeted and efficient approaches to enhance crop resilience and productivity. Plants have evolved robust defense mechanisms against pathogen attack that are triggered by the initial recognition of the pathogen. This recognition leads to a cascade of signaling responses known as Pathogen-Associated Molecular Pattern (PAMP) Triggered Immune (PTI) response, eventually resulting in changes in the gene expression of the host (Kankanala *et al*., 2019). Applying advanced genomic research, such as in underutilized legume crops in sub-Saharan Africa is expensive, however their resilience potential could be realized (Abberton *et al*., 2022).

In the leguminosae family, two model legumes, *Medicago truncatula* and *Lotus japonicas*, have been used to advance the genomic study of legumes (Zhu *et al*., 2005). Based on these model legumes, several genetic and genomic resources have been developed to assist breeding programs to enhance tolerance and resistance to abiotic and biotic stresses in legume crop species. The genome sequences of several legume crops, such as soybean, groundnut, common bean, chickpea, cowpea, peanut, lentil and mung bean can be accessed at LegumeInfo, facilitating targeted crop improvement and efficient approaches for resilience and productivity (Bevan *et al*., 2017).

According to Kole *et al*. (2015), genomics offers tools to address the challenge of increasing food yield, quality and production stability through advanced breeding techniques. Mukankusi *et al*. (2019) demonstrated that genomic technologies enable the identification and characterization of biotic resistance genes and the functional characterization of their products.

In East Africa, where legume crops like cowpea and common bean are crucial for food security for small -scale farmers, genetic improvement is still in its early stage. There is a growing need for legume varieties that can withstand various environmental challenges. Ji *et al*. (2019) highlighted the use of CRISPR/Cas9-mediated genome editing to target the symbiotic nitrogen fixation (SNF) gene in cowpea. By customizing guide RNAs (gRNAs) targeting symbiosis receptor-like kinase (SYMRK), the authors achieved about 67% mutagenic efficiency in hairy-root-transformed plants, and completely blocked nodule formation in mutants with disrupted alleles. This result demonstrates the applicability of the CRISPR/Cas9 system in cowpea, potentially stimulating functional genomics analyses for important agronomical traits in legumes.

For common beans, Viter *et al.* (2022) reported the identification of two SNPs, Chr03_39824257 and Chr03_39824268, as the strongest markers associated with resistance to ashy stem blight (ASB). The drought-sensitive gene *Phvul.003G175900* was recognized as a candidate for ASB resistance in recombinant inbred lines (RIL). Another study on the genetic mapping and inheritance of anthracnose resistance in common bean by Gomes-Messias *et al.* (2022) revealed that anthracnose resistance in the Andean bean cultivar *BRSMG Realce* is controlled by a major resistance gene, *Co-Realce*, located on chromosome Pv04. SNP markers snp1327 and snp12782, flanking this gene, have a selection efficiency of 99.2%, making them suitable for marker-assisted selection (MAS). Conversion of these molecular SNP markers to cleaved amplified polymorphic sequences (CAPs) or KASPar assays, and Illumina Veracode, will enable their wider application in legume crop improvement programs.

Kaur *et al.* (2023) reviewed advances in research on managing diseases and pests in grain legume crops. They compiled findings on host-pathogen interactions, germplasm characterization using modern genomics and phenomics tools and employed these novel approaches for disease and pest resistance in legumes for crop improvement. Furthermore, the most common diseases of legumes include powdery and downy mildews, Botrytis grey molds, root rots, Ascochyta blights, anthracnose, rusts, wilts, bacterial blights, and mosaic diseases. Damages caused by nematodes, parasitic weeds, and chewing/sap-sucking insects like pod borers and whitefly add to the constraints on legume production. Hence, genetic and genomic research has been highlighted as a crucial tool in addressing these challenges.

Advances in genomics, such as next-generation sequencing (NGS) technologies, have enabled the identification of marker-trait associations and a better understanding of the genetic basis of important traits in crops. These advancements have the potential to revolutionize crop improvement and contribute to the development of climate-resilient crops (Varshney *et al*., 2018). Integrating genetic and genomic approaches in crop improvement has the potential to enhance the resilience of cowpea, common beans and other staple food crops, thereby contributing to food security, sustainable agriculture, and the well-being of vulnerable farming communities in especially Sub-Saharan Africa.

The Need to Identify Biological Nitrogen Fixation (BNF) Genes in Legume Crops. Current challenges such as drought and heat stress significantly impact legume production and productivity in many agroecological regions of the world. In sub-Saharan Africa, legumes are integral to building resilience to climate change and ensuring food security in smallholder farming systems (Munjonji *et al*., 2018). Drought reduces legume yields by shortening the reproductive stage, reducing branching and the number of pods, and decreasing seed weight and seeds per pod (Dogan *et al*., 2007).

Nitrogen (N_2) is one of the key drivers of global agricultural production. For agricultural systems to produce the world's food, animal feed and industrial products, plants require mineral N_2 between 150 and 200 million tonnes year^{-1}. For this, it is crucial to effectively exploit and utilize the biologically fixed N_2 in agricultural systems (Unkovich *et al*., 2008). However, BNF is constrained by water stress as drought affects rhizobia growth and nodule formation (Zahran, 1999). Legumes species that maintain a relatively high

BNF under drought were reported to produce higher yields compared to those that had restricted BNF under drought (Daryanto *et al*., 2015).

Among the underutilized grown legume crops in sub-Saharan African, cowpea is considered more tolerant to drought stress due to its ability to maintain a high shoot water status under drought conditions compared to soybean and common bean (dry bean) (Hall, 2012; Rivas *et al*., 2016). Cowpea is commonly grown as an intercrop with cereals, serving as a mulch, and a good weed suppressant (Harrison *et al*., 2006; Wang *et al*., 2006). It also improves soil fertility through BNF (Bado *et al*., 2006; Nyemba and Dakora, 2010; Mogale *et al*., 2023), serves as key source of protein for rural communities and provides forage for livestock (Dakora, 2013; Dakora *et al*., 2015).

Variation in N_2 fixation is observed between legume species and genotypes due to varying environments with various biotic and abiotic factors including soil moisture and temperature, level of mineral nutrients in plant rhizosphere, soil mineral nitrogen, varietal differences, as well as the presence of size and efficacy of root nodule bacterial populations in the soil (Dakora and Keyaz, 1997). The term 'fixation' here denotes the conversion of inert atmospheric nitrogen into a biologically accessible form, thus fortifying the soil's nutrient content (Morgan, 2023).

The Nitrogen fixed by the BNF process reduces the production costs, Green House gas (GHG) emissions, and pollution of surface and ground water. A comprehensive study showed that, the efficiency of biologically fixed N_2 is greater than that of the N_2 fixed by the synthetic nitrogen fertilizers (Lassaletta *et al*., 2014). Among all the microorganisms involved in BNF process, rhizobia-legume symbiosis is the most significant and important pathway for nitrogen availability in agricultural fields (Herridge *et al*., 2008).

The genes responsible for nitrogen fixation in legumes have been identified as *nod*, *nif*, and *fix* genes (Fischer, 1994; Lindström, n.d). These genes play a crucial role in the nitrogen fixation process by encoding proteins involved in the formation and functioning of nodules. Identifying these nitrogen fixation genes in legumes is important for several reasons. Firstly, it provides insight into the molecular mechanisms underlying nitrogen fixation, allowing for a better understanding of this complex process and potentially leading to the development of improved nitrogen-fixing symbioses. Secondly, identifying these genes can aid in the selection and breeding of legume crops with enhanced nitrogen fixation ability, ultimately leading to increased crop yields and reduced dependence on synthetic fertilizers. Therefore, host plant breeding is essential to improve BNF, especially when if inoculation with elite strains is expected to increase yield. Efforts to prioritize BNF in plant breeding could significantly enhance symbiotic performance (Vanlauwe *et al*., 2019). For many decades, there has been no strong program aimed at breeding legumes, especially for BNF. However, it has been demonstrated that phosphorus (P) is a critical nutrient for optimal BNF and legume growth.

BNF, commonly studied in the context of legume -rhizobia symbiosis, is a key component of the nitrogen cycle in nature (Vlk *et al*., 2022). In fact, BNF is a process whereby plants acquire atmospheric nitrogen through interaction with bacteria capable to convert this molecular nitrogen to ammonium, which is used later for sustainable agriculture and environment. Despite its potential in plant breeding and many years of research, information is still lacking as to the regulation of hundreds of genes connected with plant–bacteria interaction, nodulation, and nitrogen fixation (Vlk *et al*., 2022).

There has been on-going research initiated to elucidate regulation of genes involved in plant-bacteria interactions. For example, Ghodake *et al*. (2023) studied the potential for enhancing BNF efficiency. Indeed, Seido *et al*. (2019) reported that BNF efficiency in cowpea can be easily enhanced using autogamous breeding methods and Vlk *et al*. (2022) found 491 differentially expressed genes connected with BNF efficiency. However, there is limited understanding of the specific genes associated with BNF efficiency in cowpea genotypes. Further research is needed to identify these genes and improve BNF efficiency in cowpea.

Conclusions

Nowadays legumes are considered as the most agriculturally and environmentally sustainable crops for both developed and developing countries, particularly in small scale farming systems. Hence, promoting the cultivation and utilization of resilient legumes in Africa particularly, is essential for sustainable agriculture and food security in the continent. Legumes have numerous roles on improving soil fertility, enhancing crop rotation, providing sources of forage for livestock, and nutritious protein sources for human consumption. By prioritizing the development and adoption of resilient legume varieties, African farming societies can increase their resilience to climate change, reduce dependence on synthetic inputs, and improve their livelihoods. Additionally, fostering partnerships among researchers, policymakers, and farmers will be crucial to ensuring the successful adoption and dissemination of resilient legume technologies. Therefore, it is crucial to search for resilient legume cultivars that can naturally fix nitrogen and therefore provide opportunity for transforming African agriculture from subsistence to sustainable development and addressing the challenges of food and nutrition insecurity in the continent.

In the face of climate change, burgeoning populations, and evolving agricultural challenges, resilient legume crops offer an inspiration hope for sustainable food production and security in Africa. This can be achieved by harnessing the power of genetics and genomics research tools. For instance, the genetic and genomic studies on cowpea and common bean crops have demonstrated the potential for developing resilient crop varieties for sustainable agriculture and feeding in Africa. Identifying biologically nitrogen fixing genes and anthracnose resistance genes in some varieties of cowpea and common bean are among the fancied genomic results. Together with improved selection and breeding techniques, varieties with high-yield, pest and disease resistance, and climate resilient would be identified, improved and deployed in appropriate agroecologies. Therefore, by harnessing the power of genetics and genomics, we can improve agricultural productivity, enhance food and nutrition security and in so doing increase the incomes and uplift the livelihoods of smallholder farmers in Africa. The continued investment in research and development in this area will play a crucial role in overcoming the challenges faced by the agricultural sector and help in creating a more sustainable future for the continent. However, it is essential to bridge the gap between scientific innovation and on-the-ground application, ensuring that the benefits of genetic and genomic research directly translate into tangible outcomes for smallholder farmers.

In conclusion, genetics and genomics studies on cowpea and common bean crops have the potential to significantly enhance sustainable agriculture and food security in Africa. By advancing resilient legumes through these studies, we can develop crops that are more adaptable to changing environmental conditions, more resistant to pests and diseases, and more nutritious in terms of human consumption. With continued investment in research and development in this area, we can also help to ensure a more secure and prosperous future for African farmers and communities.

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The Authors declare No Conflict of Interest in this paper.

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