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Underutilised Legumes for Advancing Climate-Smart Agriculture in Sub-Saharan Africa

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ABSTRACT

Sub-Saharan Africa faces intersecting challenges of food insecurity, malnutrition and climate variability, exacerbated by the predominance of rainfed agriculture and limited input use. Climate-smart agriculture (CSA) offers a framework to address these issues through increased productivity, enhanced resilience and reduced environmental impact. Underutilised legumes such as Bambara groundnut (*Vigna subterranea*), tepary bean (*Phaseolus acutifolius*) and pigeon pea (*Cajanus cajan*) present untapped opportunities for advancing CSA objectives. This review synthesises current knowledge on their physiological and agronomic traits such as drought tolerance, nitrogen fixation, short growth cycles and seed priming responses that support climate adaptation in dryland systems. Despite their potential, these legumes remain marginal in formal seed systems, research investment and public policy. Key gaps include limited field-based evaluations, underdeveloped seed and market systems and weak institutional support. The review suggests a whole-of-system approach linking research, extension and policy to scale these crops as strategic assets for resilient, inclusive and nutrition-sensitive food systems in sub-Saharan Africa.

1 | Introduction

The escalating climate crisis poses urgent challenges to global food systems, with sub-Saharan Africa (SSA) being particularly vulnerable because of its reliance on rainfed agriculture and the prevalence of resource-constrained smallholder farming (Lefe et al. 2024). The Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (2007) projected that, in the absence of emission-reduction strategies (IPCC 2007), global temperatures could rise by 1.6°C–6.9°C by the end of the 21st century (Sanderson et al. 2011). In SSA, increasing climate variability, which is marked by more frequent droughts and erratic rainfall, has already begun to disrupt agricultural productivity and rural livelihoods (Kotir 2011).

At the same time, the region continues to grapple with the dual challenges of persistent food insecurity and malnutrition (Harper et al. 2022; Christian and Dake 2022; Nel and Steyn 2022; Santos et al. 2023). These converging threats underscore the need for adaptive agricultural strategies that simultaneously enhance resilience, improve food and nutrition security and minimise environmental impacts. In this context, climate-smart agriculture (CSA) has emerged as a guiding framework, with three key objectives: (i) increase productivity, (ii) build resilience to climate stress and (iii) reduce greenhouse gas emissions (FAO 2010).

CSA is closely aligned with several of the United Nations Sustainable Development Goals (SDGs) (FAO 2019), particularly SDG 2 (Zero Hunger), SDG 13 (Climate Action), SDG 12

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(Responsible Consumption and Production) and SDG 3 (Good Health and Well-being). With less than a decade remaining until the 2030 deadline, implementing locally relevant, nutrition-sensitive and environmentally sound interventions is imperative. However, although many CSA-aligned innovations exist on paper or in trial settings (Long et al. 2016; Dossou-Yovo et al. 2024; Makate 2019), their practical uptake often falls short, due in part to institutional silos (Louwaars et al. 2013), weak value chains, limited market demand (Dossou-Yovo et al. 2024) and fragmented policy support (Sanogo et al. 2023).

Underutilised legumes such as Bambara groundnut (*Vigna subterranean* (L.) Verdc.), tepary bean (*Phaseolus acutifolius* A. Gray) and pigeon pea (*Cajanus cajan* L.) offer significant but underexplored potential for advancing CSA objectives in dryland SSA (Mijena et al. 2024; Rani et al. 2023). These crops adapt well to harsh environments, require minimal external inputs and provide important nutritional benefits. Their ability to fix atmospheric nitrogen, tolerate drought and contribute to diversified diets aligns closely with the core principles of CSA. Yet, despite growing scientific interest, they remain neglected in formal seed systems, largely absent from commercial markets and rarely prioritised in policy or private sector investment (Rani et al. 2023). Their promotion has been heavily skewed towards smallholder and subsistence contexts, which, although important, limits their visibility and potential as mainstream crops that can benefit the wider food system (Conti et al. 2019).

Moreover, the translation of research into practice has been inconsistent. Promising traits and varieties identified through academic studies or participatory trials often fail to reach broader farming communities because of a lack of continuity, limited extension support and weak linkages between research institutions, policymakers and markets (Naveena et al. 2016; Padulosi et al. 2013). Consumers are often unfamiliar with these crops, despite emerging innovations using Bambara groundnut, for example, in flour (Nwadi et al. 2020), biscuits (Abu-Salem and Abou-Arab 2011) and weaning foods (Oyeyinka et al. 2021). These creative efforts remain disconnected from formalised value chains, and the absence of coordinated investment and marketing impedes scale-up (Nwadi et al. 2020).

This review investigates how these three legumes can contribute to the advancement of CSA in dryland systems. It synthesises current knowledge on their physiological and agronomic traits related to climate resilience, including root system architecture, water-use efficiency (WUE) and osmotic adjustment. In addition, the review evaluates the use of seed priming, particularly for Bambara groundnut, as a low-cost technique to improve crop establishment and performance under drought-prone conditions.

Although these legumes strongly align with CSA principles, research on their practical integration into climate-resilient farming systems remains limited. For crops like Bambara groundnut, early growth challenges such as poor emergence and slow establishment persist, yet seed priming as a low-cost intervention remains underexplored, especially under field conditions across SSA. In contrast, tepary bean and pigeon pea show inherent vigour during establishment but have received relatively less attention in physiological trait analysis despite their proven drought tolerance.

By consolidating existing evidence and identifying areas for future research, such as seed enhancement techniques for Bambara groundnut, or the need for multitrait evaluations under real-world conditions, the review contributes a targeted framework for repositioning underutilised legumes as viable, underused assets in advancing CSA objectives. It also supports broader progress towards the SDGs, while acknowledging the urgent need to connect smallholder realities with national and regional food system strategies.

2 | CSA

CSA has emerged as a leading framework for addressing the interconnected challenges of food insecurity, climate change and environmental degradation in agriculture. Its threefold objective is to increase agricultural productivity sustainably, enhance resilience to climate-related shocks and reduce greenhouse gas emissions, which renders it particularly relevant to dryland farming systems in SSA (FAO 2010).

The FAO (2019) report underscores CSA as a holistic and integrative approach that directly aligns with the 2030 Agenda for Sustainable Development, notably SDGs 2, 3, 12 and 13. It affirms CSA's three core pillars: (i) productivity enhancement, (ii) climate resilience and (iii) mitigation of greenhouse gas emissions, as critical levers for transforming food systems in dryland regions. CSA is especially important in developing contexts such as SSA, where agriculture remains central to GDP and livelihoods, yet is highly vulnerable to climate variability (Abegunde et al. 2019). For SSA, where the effects of climate change are already compounding structural food system challenges, CSA offers a pathway to align climate adaptation with nutrition-sensitive and locally grounded interventions (Talucder et al. 2024).

CSA encompasses adaptive agricultural practices that promote sustainable productivity gains while trying to optimise benefits and reduce trade-offs across its core objectives (Lipper et al. 2014). When adopted holistically within farming systems, CSA practices provide multiple benefits for smallholder farmers, including enhanced resilience, livelihoods and incomes (Totin et al. 2018). Fundamentally, CSA is designed to support farmers in adapting to climate change while mitigating its potential negative impacts on agricultural production and rural livelihoods (FAO 2013).

Farmers in SSA have adopted various strategies to enhance productivity and adapt to changing climatic conditions, many of which align with CSA principles (Serdeczny et al. 2017). In regions with limited rainfall, for example, farmers are increasingly replacing water-intensive crops with more drought-tolerant alternatives (Ngwira et al. 2012). In flood-prone areas, there has been a shift towards short-cycle crops, whereas other adaptation strategies include crop diversification, altered planting dates and mixed cropping systems (Ngwira et al. 2013). These practices are evidence of the multidimensional goals of CSA by enhancing both productivity and resilience under climatic stress.

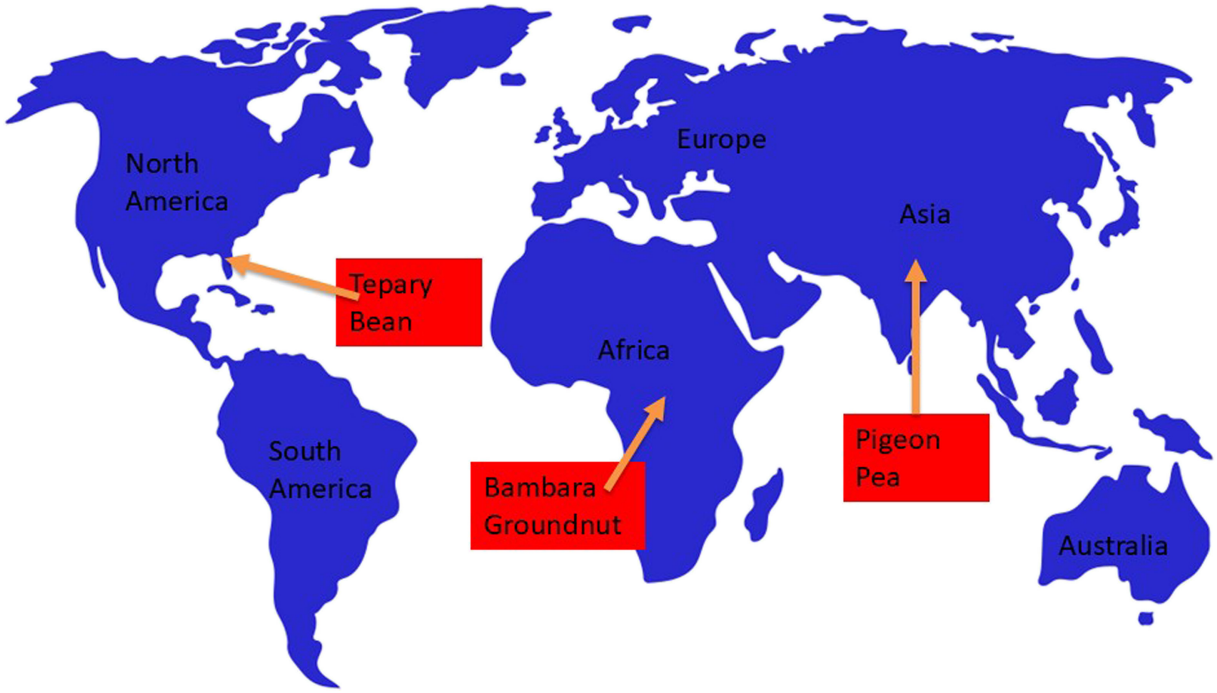


FIGURE 1 | Agroecological origins of the focal legumes (map sourced from freepix copyright free).

There is growing recognition that underutilised crops, particularly those resilient to drought, low-input conditions and soil degradation, can significantly contribute to achieving CSA outcomes (Rani et al. 2023). Though often overlooked in formal agricultural systems, their biological traits and nutritional value offer promising solutions to address climatic and food system vulnerabilities (Conti et al. 2019).

Legumes have garnered attention because of their capacity to fix atmospheric nitrogen, improve soil health, diversify diets and serve as important protein sources. These traits align with CSA's productivity, resilience and mitigation pillars (Mijena et al. 2024). See Figure 2 for a conceptual overview of how key traits of underutilised legumes contribute to CSA objectives.

The following section explores the case for focusing on underutilised legumes in CSA. This review highlights three key examples (Bambara groundnut, tepary bean and pigeon pea) and explains their potential as climate-smart crops for dryland regions.

3 | The Potential of Underutilised Legumes in CSA

Underutilised legumes include a wide range of species that have historically received limited attention in research, breeding and agricultural development strategies, despite their adaptation to marginal environments and contribution to food and nutritional security (Ayilara et al. 2022; Bhat and Karim 2009; Cheng et al. 2019). Examples of these legume species include African yam bean (*Sphenostylis stenocarpa* Hochst. ex A. Rich.), Kersting's groundnut (*Macrotyloma geocarpum* (Harms) Maréchal & Baudet), marama bean (*Tylosema esculentum* (Burchell) A. Schreiber), cowpea (*Vigna unguiculata* (L.) Walp), jack bean (*Canavalia ensiformis* (L.) DC) and lima bean (*Phaseolus lunatus* L.) (Ayenan and Ezin 2016; Bhat and Karim 2009; Padulosi et al. 2013). Each legume has unique climate-resilient traits and nutritional profiles that can contribute to more diversified, sustainable food systems in SSA.

This review focuses on Bambara groundnut, tepary bean and pigeon pea for three key reasons. First, each crop has a growing, though still limited, body of scientific literature examining traits relevant to CSA, such as drought tolerance, nitrogen fixation and seed nutrient composition. Second, they represent varied agroecological origins (Figure 1) originating respectively from Africa, North America and South Asia. These legumes exemplify parallel evolution in their adaptation to arid and semi-arid environments (Moghaddam et al. 2021). Despite their distinct phylogenetic lineages and geographic origins, they have independently developed similar adaptive traits such as deep rooting systems, efficient water use and robust nitrogen-fixing capabilities; these traits enable them to thrive under drought and heat stress conditions (Upadhyaya et al. 2012; Marthandan et al. 2020). This convergence offers valuable insights into varied adaptation pathways and the potential for cross-regional strategies in legume improvement. Third, all three crops show promise for integration into dryland smallholder systems, yet remain underrepresented in commercial seed systems, extension programmes and national agricultural research agendas.

3.1 | Bambara Groundnut

Bambara groundnut is an indigenous African legume well adapted to dryland farming systems. It has the ability to thrive in nutrient-poor soils, under low-input conditions, and it is noted for its high drought tolerance (Mayes et al. 2019). In terms of overall seed composition, Bambara groundnut seeds typically

contain approximately 60%–65% carbohydrates (mainly starch), 18%–24% protein and around 6%–7% fat, placing it nutritionally in the mid-range of grain legumes but significantly higher in protein and micronutrients than cereals (Hlanga et al. 2021; Tan et al. 2020). The seeds are the primary edible part and can be consumed fresh or dried, offering dietary versatility particularly suitable for subsistence farmers in arid and semi-arid regions (Tan et al. 2020).

Agronomically, Bambara groundnut exhibits several traits that align with CSA objectives. Its root system is both deep and extensive and dependent on the agronomic region where it is grown. Mateva et al. (2020) report that landraces from drier regions such as SSA generally have longer taproots and greater root length distribution in deeper (60–90 cm) soil depths. In contrast, landraces from wetter regions like Southeast Asia and West Africa exhibit relatively shallow and highly branched root growth closer to the soil surface. The crop has a relatively dense, closed canopy under optimal spacing, which helps reduce soil evaporation and contributes to improved WUE and weed suppression (Olanrewaju et al. 2022). Despite these favourable traits, the crop is still largely cultivated as genetically diverse landraces, with limited availability of improved or commercial varieties, which constrains breeding efforts and yield consistency (Aliyu et al. 2014). A notable agronomic constraint is its hard seed coat, which delays germination and reduces emergence rates, a barrier particularly problematic under erratic rainfall and shortened planting windows (Mandizvo and Odindo 2019).

Bambara groundnut is a fast-growing crop that requires warm temperatures and cannot tolerate frost during the growing season. Depending on the variety, it typically matures within 110–150 days (Gerrano et al. 2021). These characteristics make it an ideal candidate for seed priming interventions, which can improve early emergence and seedling vigour, and further enhance its suitability for integration into low-input, climate-resilient agricultural systems.

3.2 | Tepary Bean

Tepary bean, native to the arid regions of the south-western United States and north-western Mexico, is increasingly recognised as a climate-resilient legume (Porch et al. 2017). It is predominantly cultivated in arid and semi-arid environments because of its tolerance to heat and drought (Rao et al. 2013). The crop is also resistant to many pests and diseases and is widely used in common bean (*Phaseolus vulgaris*) improvement programmes as a source of genetic variation for abiotic stress tolerance.

In SSA, tepary beans are cultivated mainly by smallholder farmers under poor soils and low-input conditions (Jiri and Mafongoya 2016). Research has highlighted several advantageous agronomic traits of the species that make it suitable for dryland farming systems. For example, it has a short growth cycle, with emergence occurring within 5–10 days and maturity typically reached within 60–120 days (Jiri and Mafongoya 2016; Ghadimian et al. 2021). Tepary beans also develop a deeper taproot compared with common beans; although the latter reaches depths of 0.5–1 m, tepary bean roots can extend up to twice as deep, enhancing their ability to access subsoil moisture (Burridge et al. 2020). In addition, it demonstrates high WUE, a critical trait under conditions of moisture stress (Mhlaba et al. 2018). Although these attributes confer inherent resilience, productivity remains limited where unimproved or recycled seed is used. The development and adoption of improved varieties could significantly enhance performance and yield consistency under such marginal conditions.

Tepary bean fixes atmospheric nitrogen through symbiosis with *Rhizobium* sp. strain R3254, contributing up to 260 kg N ha^{-1} after inoculation and improving soil fertility (Ullah 2010). Nutritionally, it is rich in protein, with content ranging from 23% to 25%, comparable with other grain legumes (Mwale et al. 2020). The dry grains are consumed in stews, soups or with maize, whereas the leaves, though tougher, are also edible (Albala 2011).

Despite its potential, tepary bean remains underutilised in formal agricultural systems. Its resilience, soil-enriching capacity and nutritional value align well with the pillars of CSA, warranting greater attention in research, breeding and policy to support sustainable farming in resource-limited settings.

3.3 | Pigeon Pea

Pigeon pea is a drought-resilient legume originally domesticated in Asia but now widely cultivated in tropical and subtropical regions, particularly across SSA (Saxena 2008). It thrives in marginal environments characterised by low soil fertility and erratic rainfall, making it well suited for smallholder farming systems (Chisa et al. 2021). One of its notable traits is a deep root system, reaching depths of 1–2 m, which allows the plant to access subsoil moisture during dry periods (Fernandes et al. 2023). Pigeon pea is also commonly intercropped with cereals such as maize and sorghum, improving land-use efficiency and contributing to system resilience through complementary nutrient and water use (Fernandes et al. 2023).

Pigeon pea contributes significantly to soil health, functioning as a biological soil ameliorant. It enhances soil nitrogen levels through biological nitrogen fixation (BNF) and leaf litter, contributing between 40 and 60 kg N ha^{-1} to the soil annually (Ansari and Mahmood 2017; Kizito 2018). The crop performs well on degraded soils and can stabilise yields under moderate drought conditions (Bakala et al. 2024). A key feature of pigeon pea is its wide range of maturity durations, which vary by cultivar. Early-maturing varieties reach maturity in approximately 90–145 days, whereas medium- and long-duration types can take up to 250–300 days (Saxena 2008; Singh et al. 2018). Long-duration cultivars, although beneficial in extended growing seasons, are vulnerable to winter frost damage, particularly when grown in areas with late-season cold spells. In contrast, short-duration, high-yielding cultivars, many developed by ICRISAT, are better suited to multiple cropping systems under both rainfed and irrigated conditions. These genotypes are less sensitive to photoperiod, can escape end-of-season drought and offer flexibility

TABLE 1 | Summary of the comparative traits of Bambara groundnut, tepary bean and pigeon pea, highlighting their unique and overlapping contributions to climate-smart agriculture.

Trait/function	Bambara groundnut	Tepary bean	Pigeon pea
Native origin	Africa	Americas	Africa/Asia
Drought tolerance	High	Very high	Moderate–high
Root architecture	Deep, extensive	Deep	Deep
Nitrogen fixation	Yes	Yes	Yes
Nutritional value	High protein, balanced amino acids	High protein, micronutrients	High protein, fibre
Growth cycle	Medium (90–150 days)	Short (60–90 days)	Medium–long (90–300 days)
Adaptability to poor soils	High	Moderate–high	High
Canopy cover/soil moisture use	Closed canopy, reduces evaporation	Moderate canopy	Moderate canopy
Seed priming response	Good	N/A	Limited
Use in intercropping	Limited	Limited	Common with cereals

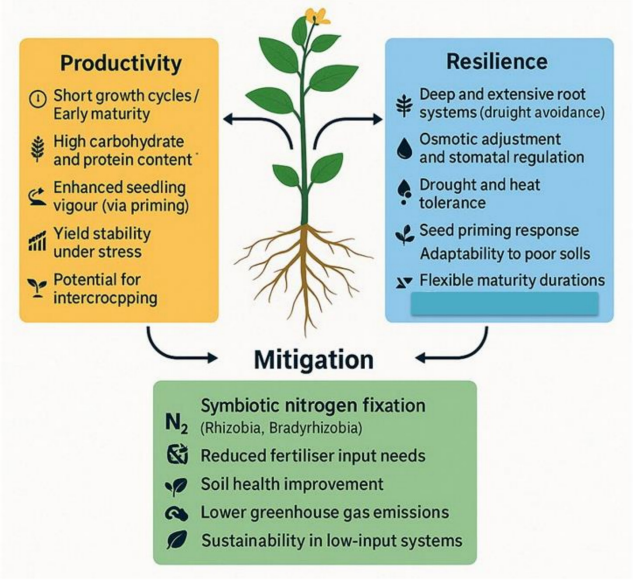


FIGURE 2 | Functional traits of underutilised legumes aligned to climate-smart agriculture objectives (adapted from Ayilara et al. 2022).

in cropping calendars by allowing farmers to grow a second crop such as wheat, barley, mustard or chickpea after harvest (Singh et al. 2018).

Nutritionally, pigeon pea is a valuable legume, particularly for regions where diets are predominantly cereal-based and prone to protein-energy malnutrition. The dry seeds contain approximately 20%–22% protein, offering a vital plant-based protein source for low-income households (Adjei-Nsiah 2012). In addition to protein, pigeon pea is rich in dietary fibre (about 15 g per 100 g), which supports digestive health and glycaemic regulation (Haji et al. 2024). The seeds also provide essential micronutrients, including iron (5.2 mg/100 g), magnesium (183 mg/100 g), phosphorus (367 mg/100 g) and potassium (1392 mg/100 g), all of which play important roles in oxygen transport, neuromuscular function and bone mineralisation (Kunyanga et al. 2013; Haji et al. 2024).

The seeds are commonly consumed boiled, split as dhal or incorporated into traditional dishes such as stews and porridges. Additionally, in some regions, the young pods and leaves are eaten as vegetables, contributing to dietary diversity and increased micronutrient intake (Fernandes et al. 2023; Chisa et al. 2021).

Although ICRISAT has progressed in breeding for stress tolerance and disease resistance (Varshney et al. 2010), most farmers still rely on unimproved landraces with suboptimal traits (Hluyako et al. 2017). Greater investment in breeding, farmer outreach and value chain development is essential to unlock pigeon pea's full potential as a climate-smart crop in SSA.

Together, these three legumes illustrate the diverse pathways through which underutilised crops can support the CSA agenda. The following section will examine the physiological and agronomic traits that underpin their performance under stress and highlight their alignment with the CSA pillars of productivity, resilience and mitigation (Table 1).

4 | Key Traits Supporting Climate-Smart Functions

Underutilised legumes exhibit key physiological and agronomic traits—such as deep root systems, osmotic adjustment, stomatal regulation, nitrogen fixation, short growth cycles and seed priming response—that make them highly suitable for dryland farming in SSA. These traits are particularly aligned with the goals of CSA (Figure 2), which aims to increase productivity, enhance resilience to climate variability and reduce environmental impact. In contexts of erratic rainfall, poor soils and limited inputs, these traits are not just advantageous but essential for crop survival, rapid establishment and consistent yields under stress.

This section explores how these traits contribute to one or more CSA pillars, offering insight into their functional value and practical relevance. It also identifies key knowledge gaps, particularly in comparative field research and varietal performance, that must be addressed to maximise the full potential of underutilised legumes in sustainable agriculture.

4.1 | Deep Root Systems

Deep and extensive root systems are among the most critical drought-resilience traits observed in underutilised legumes such as Bambara groundnut, tepary bean and pigeon pea. These systems allow the crops to access water from deeper soil horizons, enhancing physiological stability and yield maintenance under moisture stress (Poorter et al. 2012). For instance, Bambara groundnut landraces from drier regions of SSA have demonstrated root penetration depths ranging from 60 to 90 cm, with higher root length density in deeper soil layers compared with landraces from wetter regions, which tend to have shallower, more branched roots (Mateva et al. 2020). Similarly, tepary bean taproots have been reported to extend up to 2 m, twice as deep as those of common bean, enabling superior access to subsoil moisture and improving drought escape (Burridge et al. 2020).

Pigeon pea also develops a deep taproot system, reaching 1–2 m, which allows it to maintain transpiration and growth during prolonged dry spells (Fernandes et al. 2023). This rooting strategy, when combined with its ability to persist in degraded soils, positions pigeon pea as a viable legume for agroecologies experiencing erratic rainfall patterns.

These root traits such as rooting depth, root length density and vertical distribution directly influence WUE and drought adaptation, particularly in dryland farming systems where rainfall is both unpredictable and poorly distributed across the growing season (Faverjon et al. 2019; Abdelhamid 2010). For example, the deep-rooting architecture of tepary bean contributes to its high WUE under limited irrigation and minimal soil fertility (Mhlaba et al. 2018).

Despite their evident ecological value, the root systems of many underutilised legumes remain understudied, especially under field conditions in SSA. Challenges such as limited access to high-throughput root phenotyping platforms and variability in root development across environments constrain breeding efforts for drought-adaptive ideotypes (Abdelhamid 2010). Investing in root phenotyping research, including the use of tools like rhizotrons, minirhizotrons and image-based platforms, would enable a better understanding of genotypic differences and their interaction with agroecological zones. Moreover, insights into root system architecture could inform agronomic decisions, such as plant spacing, soil amendment strategies and intercropping arrangements, to optimise moisture capture and improve system-level resilience (Mayes et al. 2019; Mateva et al. 2020).

By advancing root trait characterisation in these legumes, researchers and policymakers can better align breeding priorities and management practices with the productivity, resilience and mitigation pillars of CSA.

4.2 | Osmotic Adjustment and Stomatal Regulation

In addition to structural adaptations, underutilised legumes such as Bambara groundnut, tepary bean and pigeon pea exhibit a range of physiological mechanisms that enhance their resilience under drought and heat stress (Rao et al. 2013). Among these, osmotic adjustment and stomatal regulation play central roles in maintaining plant function when water is limited.

Osmotic adjustment involves the active accumulation of solutes such as proline, sugars and inorganic ions within plant cells to maintain cell turgor pressure (Zivcak et al. 2016). This process enables continued cell expansion and delays wilting under low water availability (Tabassum et al. 2018). Stomatal regulation, on the other hand, governs gas exchange and water loss by adjusting the opening and closing of stomata in response to environmental signals (Kaiser and Paoletti 2014). Rapid stomatal closure during water stress reduces transpirational water loss while helping to protect internal leaf structures (Marthandan et al. 2020).

Although these mechanisms are well documented in cereals and major legumes like wheat, maize and soybean, they remain less frequently studied in underutilised species. However, emerging research suggests that these processes may confer unique and significant adaptive advantages in crops like Bambara groundnut, tepary bean and pigeon pea, particularly under the resource-constrained and variable conditions typical of smallholder systems in SSA.

For example, in Bambara groundnut, certain genotypes have demonstrated enhanced proline accumulation and more efficient stomatal closure under terminal drought stress (Kundy 2019). These traits enable the crop to sustain photosynthetic activity at lower relative water content, delaying physiological shutdown and allowing continued growth and grain filling during dry periods (Muhammad et al. 2016). In practical terms, this means that certain Bambara groundnut can maintain productivity even under severe late-season drought, making it a reliable option for regions with erratic rainfall.

Tepary bean exhibits a conservative water-use strategy, characterized by lower stomatal conductance and high intrinsic WUE (Mhlaba et al. 2018; Porch et al. 2017). This means the plant loses less water through transpiration while maintaining adequate carbon fixation, allowing it to survive prolonged droughts without significant yield penalties. Such traits are especially valuable in arid regions where water is scarce and irrigation infrastructure is lacking.

In pigeon pea, stomatal sensitivity enables the plant to respond quickly to atmospheric dryness (Lobato et al. 2021). By closing its stomata, pigeon pea minimises transpirational loss while still supporting canopy cooling and reproductive development, even

under high temperatures (Bakala et al. 2024). This mechanism protects critical growth stages like flowering and pod setting from heat stress, which can otherwise lead to flower abortion and yield loss in more sensitive crops.

Beyond stomatal responses, these legumes also activate a range of hormonal and morphological adjustments under stress, such as reducing leaf surface area, increasing root-to-shoot ratios and modulating levels of abscisic acid (ABA) and other osmoprotectants (Ozga et al. 2017). These responses work in concert to protect the photosynthetic apparatus, reduce oxidative damage and ensure survival and productivity in hostile environments.

Practically, these physiological traits contribute to greater yield stability in low-input farming systems, where water stress is common and external inputs (e.g., irrigation and fertiliser) are limited. Their integration into breeding programmes offers the potential to develop drought-resilient cultivars without compromising yield. Furthermore, a better understanding of these mechanisms in underutilised legumes could guide management practices such as timing of sowing, crop spacing and intercropping design to optimise water use and support the resilience goals of CSA.

4.3 | Biological Nitrogen Fixation

Although BNF is a well-known trait across nearly all legume species, what is often more agronomically relevant is the degree of host selectivity and symbiotic efficiency with rhizobial strains. This becomes particularly important in smallholder contexts, where access to commercial inoculants is limited and synthetic fertilisers are often unaffordable (Masso et al. 2016). In such low-input systems, crops that can form effective, spontaneous associations with native rhizobia are especially valuable.

Among the underutilised legumes examined, pigeon pea stands out as the most beneficial option for smallholder farmers. It readily forms symbioses with indigenous rhizobia in many African soils and can fix between 40 and 60 kg N ha^{-1} through a combination of nodulation and nitrogen-rich leaf litter (Ansari and Mahmood 2017; Kizito 2018). Its reliable nitrogen fixation without the need for inoculation makes it a practical and accessible solution for nutrient-poor environments.

Tepary bean also shows strong potential for nitrogen fixation. It forms a symbiosis with *Rhizobium* sp. strain R3254 and has been reported to fix up to 260 kg N ha^{-1} under optimal conditions (Ullah 2010). However, such rates are rarely realised in smallholder field environments. More conservative field-based estimates place fixation at 20–50 kg N ha^{-1}, particularly under arid and semi-arid conditions where the crop is typically grown (Singh et al. 2024). Although tepary bean has demonstrated the ability to nodulate without inoculation in some soils, its effectiveness is still influenced by the availability of compatible native rhizobia. Further field-based research is needed to confirm its consistency across different agroecological zones and inform targeted inoculation strategies.

In contrast, Bambara groundnut shows greater variability in its symbiotic performance. It is known to associate with indigenous *Bradyrhizobium* strains, but nodulation efficiency depends heavily on genotype and environmental conditions (Bitire et al. 2022; Mayes et al. 2019). Reported nitrogen fixation rates range up to 28.42 kg N ha^{-1} (Fwanyanga et al. 2022) but often fall short without inoculation. As such, Bambara is less suited to spontaneous nitrogen fixation in low-input settings and would benefit from targeted inoculation strategies or breeding efforts to improve its BNF efficiency.

For smallholder farmers, the implications are clear: Understanding whether a legume requires inoculation to achieve meaningful BNF is critical for its successful adoption. Of the three crops discussed, pigeon pea offers the most consistent benefit, followed by tepary bean, whereas Bambara groundnut currently presents more limitations unless supported by interventions. Promoting legumes with spontaneous BNF capacity can reduce fertiliser costs, improve soil health and contribute to more sustainable and climate-resilient farming systems.

4.4 | Early Maturity and Cropping Flexibility

In rainfed and drought-prone agroecosystems, early maturity and cropping flexibility are essential traits that contribute to both productivity and risk reduction. These traits allow farmers to align crop cycles with short or shifting rainfall patterns, support crop diversification and reduce exposure to terminal drought. Underutilised legumes such as tepary bean, pigeon pea and Bambara groundnut exhibit varying degrees of maturity and photoperiod responsiveness, which influence their suitability for different climates and cropping systems.

Tepary bean is among the most notable for its short growth cycle, typically reaching maturity within 60–90 days (Ghadimian et al. 2021). This rapid lifecycle enables farmers to take advantage of brief rainy seasons or grow the crop between major planting windows (Mwale et al. 2020). Its ability to thrive under high temperatures and minimal water input makes it especially useful in short-season cultivation, where conventional legumes often fail. This maturity profile supports its use in relay planting, post-harvest rotations and intercropping arrangements with cereals in dryland zones.

Pigeon pea offers a contrasting example, with a wide range of maturity durations—from early-maturing improved cultivars (90–145 days) to long-duration landraces that can take up to 300 days to reach physiological maturity (Hluyako et al. 2017; Varshney et al. 2010). This diversity is largely influenced by photoperiod sensitivity and agroecological conditions. Early-maturing genotypes, developed by institutions such as ICRISAT, are particularly valuable in regions with short growing seasons or where pigeon pea is used in double-cropping systems. These cultivars allow farmers to plant a second crop such as wheat, barley, mustard or chickpea after harvest, improving land-use efficiency and food security (Nandhini et al. 2015). In contrast, long-duration types are better suited for monoculture systems in areas where land pressure is lower and rainfall is more evenly distributed throughout the year.

Bambara groundnut, however, presents a unique challenge. It is predominantly grown as genetically heterogeneous landraces,

many of which exhibit photoperiod sensitivity—particularly affecting pod development and seed filling rather than flowering. Although flowering in most genotypes occurs regardless of daylength, pod set is significantly delayed or suppressed under long photoperiods exceeding 14 h (Mubaiwa et al. 2018). This can result in asynchronous maturity, uneven harvests and poor grain quality, particularly in regions farther from the equator (Mayes et al. 2019). Moreover, long daylengths promote vegetative growth at the expense of reproductive development, likely due to altered assimilate partitioning (Gerrano et al. 2021). These physiological constraints limit Bambara groundnut's geographic adaptability and its incorporation into intensified cropping systems.

To address these limitations, targeted breeding for photoperiod-insensitive and short-duration Bambara varieties is urgently needed. Such cultivars would enable synchronised maturity, shorten the harvest window and allow for double cropping in regions with limited or erratic rainfall. Optimising maturity profiles and photoperiod responses in these underutilised legumes can help farmers better align planting decisions with climate variability, reduce harvest risk and enhance system resilience—making these crops key tools in the implementation of CSA across SSA.

4.5 | Seed Priming Response

In low-input, rainfed farming systems, rapid and uniform crop establishment is essential for productivity and climate resilience. One technique that has shown promise in enhancing early-stage performance is seed priming, a presowing treatment in which seeds are partially hydrated to activate metabolic processes without initiating radicle emergence (Bhowmick et al. 2013). Among the various approaches, hydro-priming is the simplest and most accessible; it typically involves soaking seeds in clean water for a period of hours, followed by redrying prior to planting (Ghassemi-Golezani 2008). This low-cost, farmer-friendly intervention can significantly improve germination rate, seedling vigour and emergence uniformity, especially under erratic or delayed rainfall conditions (Chisa et al. 2025).

For smallholder farmers, who often contend with low seed vigour, hard seed coats and unpredictable field conditions, priming provides a practical means to overcome establishment failures (Mandizvo and Odindo 2019; Hluyako et al. 2017). Among the legumes reviewed, Bambara groundnut has shown the most consistent and substantial response to hydro-priming. In a study by Legwaila et al. (2013), 24-h priming reduced the coefficient of variation (CV) for emergence time by 30% and improved biomass accumulation. More recent work by Chisa et al. (2025) reported a 50% reduction in days to emergence and a 60% increase in total plant dry mass after 36-h priming, compared with nonprimed controls. Such results suggest that priming helps synchronise seedling emergence, an important trait for labour-efficient crop management, particularly where timely weeding and field operations are constrained.

In contrast, tepary bean and pigeon pea generally exhibit strong emergence under favourable conditions, likely reflecting evolutionary selection for survival in arid zones. However, limited field-based evidence exists on the benefits of priming under stressful or variable environments. A study by Sajjan et al. (2017) found modest gains in seedling vigour, with pigeon pea exhibiting physiological changes including enhanced mobilisation of storage proteins like 11S globulin. These findings highlight the genotype-specific and context-dependent nature of priming responses, reinforcing the need for tailored protocols.

Although some advantages of seed priming, such as emergence uniformity, may seem relevant to commercial farming, in practice, formal systems rarely require such interventions. This is due to their reliance on high-vigour, genetically improved seed lines optimised for uniform germination (Afzal et al. 2020; Zhang et al. 2015). Additionally, 24- to 36-h soaking and drying periods may introduce delays incompatible with high-throughput planting schedules in mechanised systems (Jarrar et al. 2023).

Instead, the primary value of seed priming lies in smallholder contexts, where resource limitations and climate variability hinder consistent crop establishment. In these settings, priming offers a cost-effective and scalable tool for improving stand uniformity, reducing replanting and enhancing yield reliability, particularly in dryland agroecosystems (Devika et al. 2021; Waqas et al. 2019). For further research, the development of species- and genotype-specific priming protocols, coupled with integration into extension programmes, is essential for translating controlled-environment successes into on-farm impact.

5 | Research and Policy Gaps Hindering the Scaling-Up of Underutilised Legumes in CSA

Despite their alignment with CSA principles, underutilised legumes such as Bambara groundnut, tepary bean and pigeon pea remain marginal in formal agricultural systems across SSA. Their limited adoption is shaped by a combination of technical constraints, including gaps in breeding, agronomy and seed systems and institutional challenges such as weak policy integration, minimal extension support and underdeveloped markets (Garbero et al. 2018).

Although progress has been made in breeding and characterising traits such as drought tolerance, early maturity and nutritional content, research investment in these crops remains significantly lower than in major staples (Ghimire et al. 2022). Many varieties developed by public research institutions fail to reach farmers because of fragmented dissemination pathways, lack of commercialisation incentives and limited seed system capacity. Akpo et al. (2021) report that a percentage of farmers (80%–90%) have no access to recently released and high-yielding varieties, proving the failure of various seed delivery models implemented. Advances in modern genomics and participatory breeding offer new opportunities (Mwale et al. 2020) but require strategic investment to bridge genotype–environment gaps and accelerate domestication.

Agronomic research is also limited, with few context-specific recommendations to other regions. Seed priming of legumes such as Bambara groundnut and pigeon pea, though promising, has been widely tested in controlled settings (Ghassemi-Golezani 2008; Sajjan et al. 2017; Marthandan et al. 2020) and

TABLE 2a | Key research gaps limiting uptake of underutilised legumes.

Identified research gap	Description	Strategic research priority	CSA pillar addressed
Genotypic characterisation & breeding	Limited genomic and phenotypic data on traits like drought tolerance, maturity and nutrition	Invest in multitrait breeding across agroecological zones using modern genomic tools	Productivity & resilience
Context-specific agronomy evaluations	Limited region-specific agronomic guidelines for low-input smallholder systems	Conduct farmer-participatory trials and adaptive agronomic research	Productivity & resilience
Seed priming field validation	Most studies are conducted under controlled conditions; lack of real-world validation	Evaluate priming techniques under diverse field conditions with different landraces	Resilience
Socio-cultural barriers & limited awareness (research dimension)	Limited evidence on how perceptions and cultural preferences influence adoption	Conduct perception and consumer-behaviour studies to inform nutrition interventions	Productivity

remains under-evaluated across diverse environments and landraces. Farmer-participatory trials, genotype–environment assessments and adaptive agronomic strategies are needed to develop practical, scalable solutions.

Beyond research, systemic barriers continue to restrict uptake. Extension services are under-resourced and often unfamiliar with underutilised legumes, leading to low awareness and adoption among farmers (Akpo et al. 2021). Improved varieties may be included in seed catalogues for research purposes but are rarely available in agro-dealer networks for broader distribution (Porch et al. 2024). Smallholders continue to rely on unimproved landraces that are poorly adapted to climate variability and offer limited economic returns (Jiri and Mafongoya 2016),

Policy and institutional disconnects further impede impact. Although these crops are referenced in CSA strategies and development plans, they remain largely absent from formal procurement systems, seed subsidy schemes and nutrition-sensitive programming. Research institutions often lack the mandate or resources to ensure the long-term scaling of innovations beyond pilot projects.

Consumer awareness is another constraint. Underutilised legumes are often stigmatised as "poor people's food" and rarely feature in urban diets or school feeding programmes (Knez et al. 2023; Olanrewaju et al. 2022). Meanwhile, industrial legumes such as soybeans benefit from substantial investment, visibility and policy support (Siddique et al. 2012; De Visser et al. 2014), perpetuating dietary dependence on a narrow range of staples.

Addressing these barriers requires a coordinated, whole-of-system approach. Researchers must work alongside seed producers and agro-enterprises to commercialise climate-resilient varieties. Governments should integrate underutilised legumes into national CSA investment plans, seed strategies and public procurement schemes (Makate 2019). Donors and policymakers are increasingly recognising the role of SMEs and private-sector actors in scaling inclusive innovation, with new frameworks supporting sustainable development and smallholder empowerment (Chavez-Tafur et al. 2020; Pouw et al. 2019). Extension systems must also be capacitated to support both cultivation and consumption, particularly in nutrition-sensitive contexts.

Tables 2a and 2b summarise the key research and policy gaps hindering the mainstreaming of underutilised legumes and outline strategic priorities aligned with the CSA pillars of productivity, resilience and mitigation. By addressing both technical and institutional constraints, these crops can play a transformative

TABLE 2b | Key policy and institutional gaps limiting uptake of underutilised legumes.

Identified policy/institutional gap	Description	Strategic policy priority	CSA pillar addressed
Weak extension & farmer knowledge systems	Insufficient farmer training and access to extension services	Incorporate legumes into extension curricula and provide targeted capacity-building	Productivity
Policy & institutional disconnect	Limited coordination between research, policy and commercial pathways	Develop whole-of-system strategies linking research outputs to market and policy actions	Productivity resilience mitigation
Underdeveloped seed & market systems	Limited access to improved seed, weak processing infrastructure and low market incentives	Strengthen seed systems, support agro-processing and incentivise private-sector investment	Productivity & economic viability
Socio-cultural barriers & limited awareness (policy dimension)	Underrecognition of underutilised legumes in national food and nutrition policies	Mainstream underutilised legumes in dietary guidelines, school-feeding and public-procurement policies	Productivity

role in realising SDGs 2 (Zero Hunger), 3 (Health and Well-being), 12 (Responsible Consumption and Production) and 13 (Climate Action). Although not a panacea, mainstreaming underutilised legumes into CSA frameworks offers a scalable and evidence-based pathway to resilient, inclusive and nutritious food systems in Africa.

6 | Conclusion

Underutilised legumes hold immense potential to transform SSA's agricultural landscapes by supporting the three pillars of CSA: productivity, resilience and mitigation. Crops such as Bambara groundnut, tepary bean and pigeon pea offer unique agronomic traits, including drought tolerance, nitrogen fixation and adaptability to low-input systems, that make them particularly valuable in dryland environments. However, their contribution remains constrained by limited breeding investment, poor seed system integration, weak extension support and low consumer awareness.

A coordinated, multilevel strategy is needed to fully realise the role of these legumes in advancing CSA. This includes targeted research on trait improvement and seed priming, development of region-specific agronomic practices, market development and stronger policy alignment. Engaging the private sector, enhancing extension services and mainstreaming these crops into national development agendas will be critical.

Positioning underutilised legumes as core components of resilient and nutrition-sensitive agricultural systems is not only an opportunity but also a necessity in achieving SDGs 2 (Zero Hunger), 3 (Good Health), 12 (Sustainable Consumption) and 13 (Climate Action). Scaling their use represents a practical, evidence-based pathway towards climate-resilient, equitable and diversified food systems across Africa.

Author Contributions

A. Chisa: conceptualization, data curation, formal analysis, investigation, methodology, validation, writing – original draft, writing – review and editing. **Mutondwa M. Phophi:** writing – review and editing. **A. O. Odindo:** project administration, supervision, writing – review and editing. **P. Mafongoya:** conceptualization, funding acquisition, project administration, resources, supervision, validation, writing – review and editing.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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