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Climate-Smart Pigeon Pea Production: Genetic, Agronomic, and Socioeconomic Pathways to Resilient Legume Systems

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Pigeon pea (*Cajanus cajan* (L.) Millsp.) is a drought-tolerant, nitrogen-fixing grain legume that underpins food and nutrition security for millions of smallholder farmers across South Asia, sub-Saharan Africa, and parts of Latin America and the Caribbean. Approximately five million tonnes are produced annually on roughly six million hectares worldwide, with India, Myanmar, Malawi, Kenya, and Tanzania accounting for the great majority of cultivated area (FAOSTAT, 2021, as cited in Haji et al., 2024). International research organizations have positioned pigeon pea as a flagship "climate-smart" crop capable of simultaneously improving productivity, strengthening resilience, and contributing to greenhouse-gas mitigation through biological nitrogen fixation and reduced fertilizer dependence (CABI, 2025a; CABI, 2025b). This review synthesizes recent peer-reviewed and institutional literature on climate-smart pigeon pea production, covering genetic improvement, agronomic innovation, integrated pest and disease management, and the socioeconomic dimensions of adoption, concluding with research and policy priorities for scaling climate-smart pigeon pea systems.

Keywords: Cajanus cajan; climate-smart agriculture; drought tolerance; nitrogen fixation; intercropping; genomic selection; food security; smallholder agriculture; semi-arid tropics

Introduction

Climate change is progressively undermining the productivity of rainfed cropping systems on which hundreds of millions of smallholder farmers depend, with sub-Saharan African staple crop yields projected to decline by 10–20% by 2050 under current climate trends (Global Review of Climate Change Impacts, 2025). Legume crops, including pigeon pea, chickpea, and cowpea, are increasingly recognized as central components of climate-smart agriculture (CSA) strategies because they combine resilience to abiotic stress with the capacity to fix atmospheric nitrogen, reducing synthetic fertilizer requirements and the greenhouse-gas footprint of cropping systems (Springer, Climate Change Impacts on Legume Crop Production, 2023). Pigeon pea, also known as red gram, toor dal, or Congo pea, is indigenous to the Indian subcontinent and is the world's sixth most important grain legume by production (Haji et al., 2024). Its deep, penetrating root system gives it exceptional drought tolerance among legumes available to farmers in semi-arid environments (KALRO, n.d.), and it is highly nutritious, containing 20–28% protein along with essential amino acids, vitamins, and minerals (Haji et al., 2024; Teka et al., 2022). Despite these attributes, average global yields remain low—around 800–900 kg per hectare—far below the 1.6–1.8 tonnes per hectare attainable under improved agronomic management (Kamdi, Sawargaonkar, & Jat, 2026). Climate-smart pigeon pea production seeks to close this gap through an integrated combination of genetic improvement, agronomic innovation, and enabling socioeconomic conditions, which this review synthesizes across three pillars.

Global Production, Distribution, and Nutritional Importance

Pigeon pea is cultivated on approximately 6.1 million hectares worldwide, yielding roughly five million tonnes of grain annually (FAOSTAT, 2021, as cited in Haji et al., 2024). India dominates global production—approximately 4.3 million tonnes from 5.2 million hectares in 2021 (ICRISAT, n.d.)—with Myanmar, Malawi, Kenya, and Tanzania the other leading producers; together these five countries account for roughly 97% of global cultivated area, and Asia contributes about 90.5% of world production (Frontiers, Grain Nutrients Variability, 2022). Nutritionally, pigeon pea seed contains approximately 20–22% protein, 65% carbohydrate, 3.8% ash, and 1.2% fat, along with substantial thiamine, riboflavin, niacin, and ascorbic acid (Haji et al., 2024). It is low in saturated fat and sodium and cholesterol-free, with bioactive compounds associated with anti-inflammatory, antioxidant, and antidiabetic properties (Teka et al., 2022). Beyond direct human consumption as dhal, whole grain, or flour, green pods and leaves are used as vegetables and fodder and dried stems provide fuelwood and thatching material (Frontiers, 2022), strengthening pigeon pea's value within diversified, climate-resilient farming systems.

Climate-Smart Genetic Improvement: Breeding and Genomics

Pigeon pea's drought tolerance derives from drought-escape (early maturity), drought-avoidance (deep roots, high water-use efficiency, smaller leaflets, reduced canopy temperature), and biochemical mechanisms including accumulation of proline, soluble sugars, and antioxidant enzymes under water stress (Integrating Morpho-Physiological, Biochemical, and Molecular Genotyping, 2024). Paraheliotropic leaf movement further reduces water loss in tolerant genotypes (Silva et al., 2020), and comparative transcriptomics of contrasting varieties has linked gibberellin signaling and TIFY-family genes to differential drought responses, informing marker development (BMC Plant Biology, 2025). Deep taproots and lateral root proliferation extend water and nutrient access (Drought and Heat Stress: Insights into Tolerance Mechanisms, 2024), and pigeon pea roots can perform hydraulic lift, drawing water from deep soil layers to benefit shallower-rooted companion crops such as finger millet (Deep-Rooted Pigeon Pea Promotes Water Relations, 2020). A major breeding achievement is ICPV 25444, developed via speed-breeding at ICRISAT—the world's first extreme heat-tolerant pigeonpea variety, tolerating temperatures of 45°C while maturing in just 125 days. The platform grew 18,000 plants per season, cutting the time to bring an advanced cultivar to registration trials from seven–eight years to three–four (ICRISAT Pressroom, 2025). In Malawi, short-duration wilt-resistant varieties reduced crop duration from 220–240 to 160–180 days, contributing to a 49% increase in national pigeon pea cropping area and a 153% increase in production between 2000 and the early 2020s (GLDC/CGIAR, 2021). Genome sequencing led by ICRISAT and international partners (Varshney et al., 2012) underpins ongoing genomic selection and marker-assisted breeding for drought and disease resistance, including haplotype-based approaches that identified 23 marker-trait associations for drought-related traits (Superior Haplotypes for Haplotype-Based Breeding, n.d.). Fusarium wilt and sterility mosaic disease (SMD) remain the most economically damaging diseases, together capable of near-total yield loss and over US$300 million in annual SMD-related losses in India alone (Mapping Fusarium Wilt and Sterility Mosaic Disease Resistance, 2025). Resistant lines such as ICPL 87, C11, ICPL 81, and BDN1 combine resistance to multiple diseases (Integrated Disease Management of Fusarium Wilt, 2023), and wild Cajanus species carry broad-based SMD resistance that is transferable to cultivated pigeon pea (Sterility Mosaic Disease of Pigeonpea, 2024).

Climate-Smart Agronomic Practices

Sowing time and transplanting are among the most powerful adaptation levers available to farmers: trials in India's semi-arid tropics found transplanting increased yields by approximately 17% over direct seeding, with combined adjustments to planting dates improving resilience under both historical and projected (RCP 4.5) climate scenarios (Kamdi et al., 2026). Optimal planting density varies by cultivar maturity and canopy size, ranging from roughly 27,800 plants/ha for large-canopy cultivars to over 400,000 plants/ha for compact types (Journal of Agricultural Science, 1994), while drip-irrigated trials found that 30 cm row spacing combined with integrated fertilizer management and bed-and-residue mulching maximized nutrient uptake and soil moisture retention (Response of Pigeon Pea to Drip Irrigation and Mulching, n.d.). Intercropping is among the most extensively documented climate-smart practices for pigeon pea. In Brazil, its inclusion in maize–palisade grass systems enriched nitrogen-fixing Bradyrhizobium populations linked to improved soil health (Pigeon Pea-Mediated Soil Microbial Shifts, 2025). In Malawi, cowpea–pigeon pea intercropping with residue retention strengthened nitrogen cycling (Growing Africa, 2026), and the widely promoted "double-up" system pairs pigeon pea with groundnut, its deep taproot acting as a biological plough that breaks subsoil hardpans (MEL/CGIAR, Pigeon Pea Double Up Intercropping System, n.d.). A systematic review found legume intercropping with cereals fixed approximately 125 kg of nitrogen per hectare per season while reducing soil bulk density and erosion (Frontiers, Boosting Resource Use Efficiency, 2025). Because most pigeon pea is grown under rainfed conditions, moisture conservation is central to climate-smart production. Conservation agriculture practices retaining over 75% of residue cover reduce evaporative losses (KALRO, n.d.), mulching combined with supplemental irrigation improves yield and water-use efficiency (Response of Pigeon Pea to Drip Irrigation and Mulching, n.d.), and biochar incorporation has been shown to raise grain yield by 3–15% (Drought and Heat Stress: Insights into Tolerance Mechanisms, 2024). Biological nitrogen fixation is a cornerstone of pigeon pea's climate-smart value: field estimates suggest the crop fixes approximately 40 kg N/ha/season on its own and up to 125 kg N/ha/season in intercropped systems (KALRO, n.d.; Frontiers, Boosting Resource Use Efficiency, 2025), substantially reducing fertilizer needs in rotational systems (Kumar Rao, Dart, & Sastry, as cited in ResearchGate, n.d.).

Integrated Pest and Disease Management

Pigeon pea is attacked by more than 100 pathogens and a range of insect pests, all interacting with climate variability to affect crop losses (Development of Biotic-Stress Resistant Pigeonpea, n.d.). Fusarium wilt incidence can reach 60% at flowering, with total crop loss possible in susceptible cultivars (Mapping Fusarium Wilt and Sterility Mosaic Disease Resistance, 2025); management includes crop rotation, field solarization, and Trichoderma-based seed treatment (Wikifarmer, Pigeon Pea Diseases and Management Practices, 2023). Biological control using Pseudomonas and Bacillus strains has shown promise as an alternative to chemical fungicides (Integrated Disease Management of Fusarium Wilt, 2023). For sterility mosaic disease, roguing of infected plants and systemic insecticide treatment limit transmission by the eriophyid mite vector, though host-plant resistance bred from wild Cajanus relatives remains the most durable, cost-effective long-term strategy (Sterility Mosaic Disease of Pigeonpea, 2024).

Socioeconomic Dimensions and Farmer Adoption

Adoption of climate-smart pigeon pea technologies depends on a complex interplay of economic, social, and institutional factors. A study of 254 farmers in Greater Lira, Uganda, found that being male and relatively wealthier was associated with lower time commitment to pigeon pea-based CSA practices, and recommended affordable childcare and labor-saving technologies to support adoption (Academic Journals, African Journal of Agricultural Research, 2025). Farmer Field Schools in Zambia's Katete district have proven effective for teaching climate-smart agronomy, though limited access to certified seed and extension services remains a constraint (Teaching Good Agronomic Practices, 2025). Machine-learning-assisted risk analysis is emerging as a decision-support tool, as demonstrated in Odisha, India, where pigeon pea covers more than 133,000 hectares at an average yield of only about 1.04 tonnes per hectare (International Journal of Research in Agronomy, 2026). Market considerations also shape adoption: Nigerian farmer surveys found cooking time (58.3%) and commercial value (27.0%) were the most valued grain traits, ahead of maturity cycle (14.7%), indicating that breeding programs must balance resilience with marketability (Springer, Germplasm Exploration and Digital Phenotyping, 2026).

Future Outlook and Research Priorities

- Scale genomics-assisted and speed-breeding platforms to accelerate release of short-duration, heat- and drought-tolerant, disease-resistant cultivars adapted to diverse agro-ecologies (ICRISAT Pressroom, 2025).
- Expand systematic evaluation and conservation of indigenous landrace diversity, particularly in under-surveyed regions of West and Southern Africa, before further genetic erosion (Springer, Germplasm Exploration, 2026).
- Promote optimized sowing windows and transplanting as low-cost, immediately deployable climate adaptation options, supported by localized agro-climatic modeling (Kamdi et al., 2026).
- Strengthen extension and Farmer Field School delivery of intercropping, mulching, biochar, and conservation agriculture practices, with explicit attention to gender and labor constraints affecting adoption (Academic Journals, 2025; Teaching Good Agronomic Practices, 2025).
- Integrate digital and machine-learning decision-support tools with traditional agronomic advisory services to enable proactive, localized climate-risk management (International Journal of Research in Agronomy, 2026).
- Continue development of biological control agents and durable, multi-disease-resistant cultivars to reduce reliance on chemical pesticides (Integrated Disease Management of Fusarium Wilt, 2023; Sterility Mosaic Disease of Pigeonpea, 2024).

Taken together, these priorities point toward an integrated climate-smart pigeon pea research and development agenda that links genetic improvement, agronomic innovation, digital decision support, and socially inclusive extension delivery.

Conclusion

Pigeon pea occupies a distinctive position among the world's grain legumes as a crop whose inherent biological traits—deep rooting, drought tolerance, biological nitrogen fixation, and nutritional density—align closely with the goals of climate-smart agriculture. Evidence reviewed here demonstrates that substantial gains in resilience and productivity are achievable through coordinated investment across genetic improvement, agronomic innovation, and socioeconomic enablement. Scaling these climate-smart pigeon pea production systems will be essential not only for closing existing yield gaps but for safeguarding the food security, nutrition, and livelihoods of the smallholder farming communities who depend most heavily on this resilient and versatile legume.

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