Kirkhouse
Trust

Stress Tolerant Orphan Legumes

MONOGRAPH SERIES

Tepary Bean

(*Phaseolus acutifolius* A. Gray)

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Monograph Series

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The Kirkhouse Trust (KT) is a UK-registered charity founded by Sir Edwin M. Southern to fund the improvement of legume crops that are important for food and nutrition security in African countries and India and to promote scientific education. The origins of KT are entwined with the development of Sir Ed's molecular biology company, Oxford Gene Technology (OGT). In 1997, Oxford University assigned Sir Ed's microarray patents to OGT in exchange for 10% of the equity. In 2000, OGT's income began to grow, and KT was registered as a charity and endowed with an initial donation from the company.

KT's funding model aims to address its twin objectives of improving legume crops, which are important for smallholder farming systems in target countries and raising national scientific capacity. KT has a hands-on strategy, with a team of international scientific consultants working closely with the Principal Investigators (PIs) and students they mentor, providing technological backup as needed, and hosting PIs and students for study visits in their laboratories.

The STOL consortium was established in 2018 under the Promoting India-Africa Framework for Strategic Cooperation Initiative in partnership with the Indian Council of Agricultural Research (ICAR), Department of Agricultural Research and Education (DARE), Ministry of Agriculture and Farmers Welfare, New Delhi, India. The programme aims to facilitate the introduction and exchange of stress-tolerant orphan legume varieties among partnering Indian and African institutions and assess the relative response of selected species to the higher levels of abiotic stresses expected because of climate change. Crops have been identified as potentially having a crucial role in adapting to climate change in arid parts of Africa and India, and selected species are likely to become the focus of KT breeding programmes in the medium to longer term.

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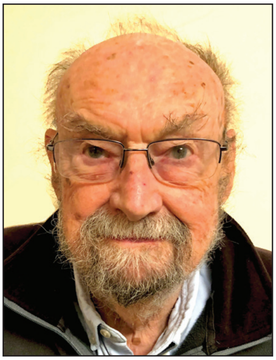


Roughly 2.5 billion people (30% of the world's population) live in semi-arid regions, and approximately a third of these people depend on agriculture for their food security and livelihood. Crop production in these regions has always faced challenges associated with excess heat, drought, a highly variable climate, land degradation, and a loss of biodiversity, which has been exacerbated in recent times by climate change, limited access to technology, poor market linkages, weak institutions, and lack of national and international partnerships. A possible strategy to cope with climate change is to switch from the cultivation of current crops to ones which are more drought-hardy. These include several minor legume crops, commonly known as orphan legumes, currently being grown to a limited extent in the drier regions of both Africa and Asia to provide food and nutritional security to households. These species have remained relatively neglected by both researchers and industry because of their limited economic importance in the global market.

To promote these orphan legumes, the Kirkhouse Trust initiated a consortium programme on "Stress Tolerant Orphan Legumes (STOL)" in partnership with several African countries and India. The STOL programme aims to facilitate the introduction and exchange of stress-tolerant orphan legume among partnering Indian and African institutions and assess the relative response of selected species and varieties to the higher levels of biotic and abiotic stresses expected because of climate change.

To facilitate the better understanding and cultivation of these new crops among Indian and African partners the STOL project is supporting the publication of a series of monographs for selected orphan legumes and Tepary Bean (*Phaseolus acutifolius* A. Gray) is one of such crops.

I congratulate the authors of this monograph Dr. Saul Eric Mwale, Senior Lecturer in Genomics and Molecular Biology, Biological Sciences Department, Mzuzu University, Malawi and Dr. Travis Parker, Assistant Professional Researcher in the Department of Plant Sciences, University of California, Davis, USA. for compiling and synthesising information to bring out the Tepary Bean monograph, which the Kirkhouse Trust is pleased to publish as part of the STOL monographs series. I am sure this publication will enlighten the policymakers, scientists, extension personnel, entrepreneurs and farmers for the improved production and consumption of Tepary Bean across Africa and Latin America.

Edwin Southern

Professor Sir Edwin M. Southern
Founder & Trustee of the Kirkhouse Trust

PREFACE

Tepary bean (*Phaseolus acutifolius* A. Gray) is a desert native crop with exceptional resistance to heat and drought. It has been cultivated in North and Central America for thousands of years, where its remarkable resistance to abiotic stresses makes it a valuable crop for ensuring food security and providing consistent returns to farmers. Beyond this, its unique region of origin subjected it to different biotic pressures compared to other related legumes, making the species a valuable source of resistance to major pests and diseases. Recent scientific advances in tepary bean have shed light on the genomic basis of valuable traits, and have led to the development of breeding materials which can be readily hybridized with other domesticates of the genus *Phaseolus*, facilitating the movement of these traits into other important germplasm.

Coming decades are set to pose several simultaneous pressures, including the need for increased food production, threats from emerging pathogens and pest pressures, and greatly increased heat and drought stress in the face of climate change. Tepary bean holds immense value in addressing each of these concurrent challenges. It has thus gained renewed interest among the research community, and is the subject of this monograph.

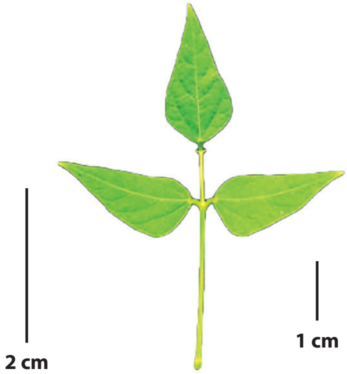
The authors would like to express their profound appreciation to the Kirkhouse Trust, including Claudia Canales-Holzeis, Robert Koebner, Prem Mathur, and Fleur Geoghegan, for providing useful comments and suggestions which helped in the development of this monograph. Paul Gepts, Jorge Berny Mier y Teran, Santos Barrera Lemus, Antonia Palkovic, Hussein Shimelis, Wilson Nkhata and Tim Porch provided useful commentary and germplasm.

The authors would also like to express their profound thanks to Sir Ed Southern, without whom this document would not be possible.

Saul Eric Mwale
Travis Parker

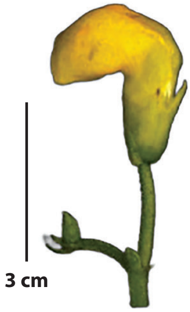
February 2025

(a) Habit

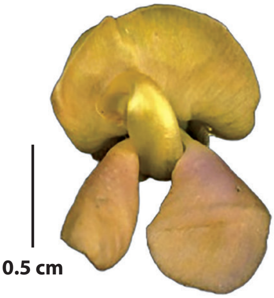


(b) Leaf

(c) Stipule



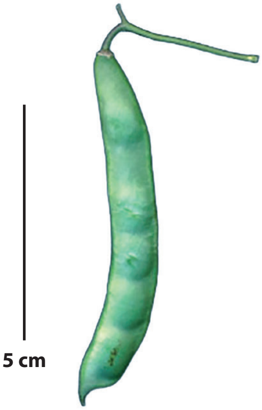
(d) Bud



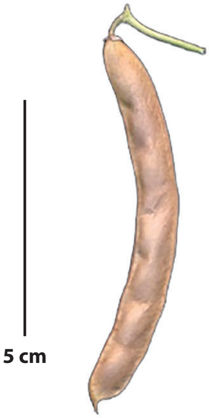
(e) Flower

(f) Standard petal

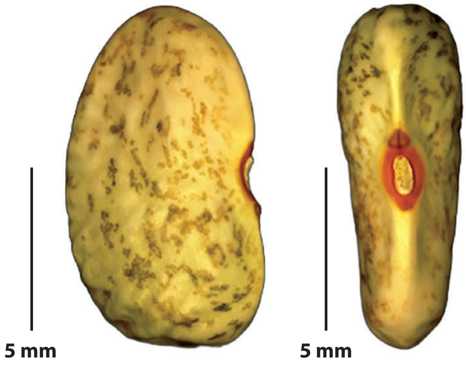
(g) Keel



(h) Immature pod



(I) Mature pod



(j) Seed

1. INTRODUCTION

Research on agricultural systems has a long history of focusing on major staple and commodity crops, while giving less attention to the enormous contribution of the numerous crop species grown on smaller land areas, particularly by subsistence farmers. These species are often called neglected and underutilized species (NUS). The capacity to support research, conservation, and use of these minor crop species is fragmented, uneven, and poorly financed. Despite this, neglected and underutilized species are mostly nutrient-dense, resilient, adapted to marginal environments, and often require fewer farm inputs for cultivation, and are therefore central to achieving global sustainable development goals. Tepary bean (*Phaseolus acutifolius* A. Gray*)* is a highly nutritious NUS with high levels of drought and heat tolerance, but to date has received relatively limited research attention. In the face of climate change, other legume staple crops are expected to become ecologically unsuited to production in many regions in coming decades (Ramirez-Cabral *et al*., 2016; Hummel *et al*., 2018; Parker *et al*., 2022). The extreme resistance of tepary bean to heat and drought makes it a critical genetic resource for providing nutritional security despite global climate change (Mwale *et al.,* 2020; Bornowski *et al*., 2023).

Here, we intend to draw attention to the genetic and economic potential of tepary bean, and to (1) describe the historical context and origin of tepary bean cultivation; (2) outline its nutritional value and potential to improve livelihoods, health, and well-being for populations facing under-nutrition, as well as those struggling with obesity; (3) relate its taxonomy and morpho-physiology to its stress tolerance attributes; (4) report its past and future potential as a source of genetic variation for common bean breeding; and (5) identify critical research gaps and possible solutions for maximum production and adoption by farmers.

2. DESCRIPTION OF THE PLANT

Tepary bean (*Phaseolus acutifolius* A. Gray, 2n = 2x = 22) is an annual herbaceous species belonging to the family Fabaceae (Leguminosae). Wild tepary beans are adapted to arid and semi-arid conditions of Mexico and the Southwestern United States. Tepary bean plants possess thick, deep taproots and often climb surrounding vegetation, exhibiting indeterminate growth (Wolf, 2018). The cultivated plants are mostly bushy, prostrate, or climbers (Wolf, 2018). Tepary bean leaves are usually trifoliate with broad or narrow lanceolate-shaped pointed leaflets. As a heat and drought response strategy, tepary beans adjust their leaflet angle depending on water, heat, and light status (Small, 2014). Tepary beans intensively exploit available soil water when it is available (Nabhan *et al*., 2020).

Tepary bean flowers are synecious, with both male and female reproductive structures in the same flower. Their corolla exhibits different colour types ranging from white, pink, or purple (Freytag and Debouck, 2002). Tepary bean flowers produce viable pollen and can set seeds at temperatures as high as 40°C. Tepary bean seeds range in colour from brown, beige, mottled, black, and cream white (Fig. 1). Pods shatter at maturity in some varieties (Pratt *et al*., 2023).

Fig. 1: Seed diversity in tepary bean. Seeds colours include white, yellow, orange, tan, brown, gray, and black; with or without mottling.

3. TAXONOMY

Tepary bean is a diploid self-pollinated species of the genus *Phaseolus*. Tepary bean is in the tertiary gene pool of common bean (*Phaseolus vulgaris*) (Gujaria-Verma *et al*., 2016). Its genome size is approximately 680 Mb (Moghaddam *et al*., 2021; Arumuganathan and Earle, 1991). Tepary bean is in the Vulgaris subgenus (Delgado-Salinas *et al*., 2006), which also includes the domesticates runner bean (*P. coccineus*) and year bean (*P. dumosus*). *P. acutifolius* includes three main sub-taxa, known as *acutifolius*, *latifolius*, and *tenuifolius*. Another closely related group, *Phaseolus parvifolius* (recently revised to *P. montanus*), is phenotypically similar to *P. acutifolius tenuifolius* types. Genetic studies using a variety of marker types have found no genetic distinction between the *acutifolius* and *latifolius* groups, but have consistently upheld the distinctness of the *tenuifolius* population and *P. parvifolius* (Arumuganathan and Earle, 1991; Gujaria-Verma *et al*., 2016; Pratt and Nabhan, 1988; Blair *et al*., 2012). A genetic continuum exists between the main *acutifolius* section and *P. parvifolius*, with *P. tenuifolius* somewhat intermediate genetically between the two (Arumuganathan and Earle, 1991; Pratt and Nabhan, 1988). *P. montanus* and *P. acutifolius* have no known reproductive barriers.

4. SPECIES ORIGIN

The crop is native to northern Mexico and the southwestern United States of America, including the Sonoran Desert (Schinkel and Gepts, 1988, 1989; Souter *et al.*, 2017, Fig. 2), and can be found in the wild from 0 to 2,300 m above sea level (Parker and Gepts, 2021). Multiple forms of evidence suggest that the crop was originally domesticated in the arid regions of northwestern Mexico (Blair *et al.*, 2002). Studies through allozyme data, phaseolin polymorphism (Schinkel and Gepts, 1988), isozyme analysis (Garvin and Weeden, 1994), amplified fragment length polymorphism (AFLP) (Muñoz *et al.*, 2006), and microsatellites (Blair *et al.*, 2012) have supported a single domestication event in tepary bean, about 5,000 years ago (Pratt and Nabhan, 1988). Multiple studies have identified the closest wild relatives of domesticated tepary beans in the Mexican state of Sinaloa (Muñoz *et al.*, 2006; Blair *et al.*, 2012), indicating that domestication may have occurred there. Archaeological findings have identified domesticated tepary beans in the Tehuacán Valley in Mexico from at least 2,500 years ago, as well as findings in Hohokam sites in Arizona by at least 1,000 years before present, indicating that they had reached these regions in pre-Hispanic times (Kaplan,

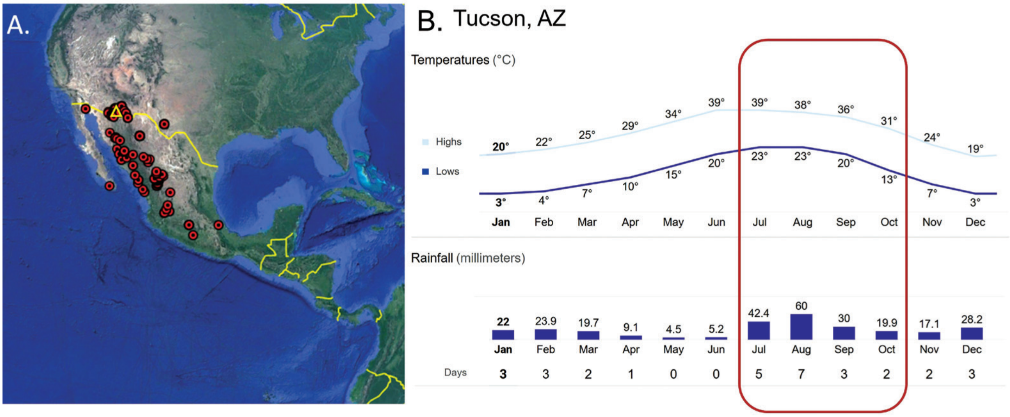


Fig. 2: Tepary bean is native to arid and semi-arid conditions of northern Mexico and the southwestern United States. (A) A map of tepary bean wild distribution in North America. Red points represent the locations of origin of wild materials in the CIAT gene bank (Genesys PGR, 2025). The yellow triangle shows Tucson, AZ, USA, at the northern end of their range. (B) Climate data for Tucson, AZ, USA. The typical growing season is indicated in red, with very high day and night temperatures, and little precipitation. Adaptation to these extreme climates make tepary beans a valuable crop for future food security.

1965; Kaplan and Lynch, 1999; Blair *et al*., 2012). Tepary beans exhibit very low rates of natural outcrossing, and domestication resulted in a major genetic bottleneck, leading to lower genetic diversity among the domesticated gene pool today (Moghaddam *et al*., 2021; Blair *et al*., 2012; Muñoz *et al*., 2006; Parker and Gepts, 2021). Wild accessions are therefore likely to hold considerable genetic diversity not currently found in the domesticated gene pool (Moghaddam *et al*., 2021; Bornowski, 2023).

5. AREAS OF PRODUCTION AND CONSUMPTION

Domesticated tepary bean is grown for its grain in scattered subtropical regions around the world, such as North and Central America, and Africa (Genesys PGR, 2025). In Africa, unimproved, low-yielding tepary bean landraces are grown by subsistence farmers under poor soil nutrient conditions (Jiri and Mafongoya, 2016; Molosiwa *et al*., 2014). In Botswana, the crop is favoured as a source of dietary protein and is widely adopted and promoted (Molosiwa *et al.*, 2014). It is also grown in certain mesic environments, such as southern Mexico and the dry corridor of Central America (Genesys PGR, 2024), where its tolerance of high nighttime temperatures, seasonal dryness, and resistance to diseases such as common bacterial blight give it a competitive advantage over other bean species. It is grown in limited quantities for its leaves and as a forage in Africa and North America (Witt *et al*., 2023).

6. PROPERTIES OF THE HARVESTABLE PARTS OF THE PLANT

Nutritional value and cooking time characteristics are essential for the adoption of crop varieties. Nutritionally, tepary bean seeds are similar to those of common bean, and are an important source of protein (24%), carbohydrates, and minerals (Porch *et al*., 2017; Amarteifio and Moholo, 1998; Bhardwaj and Hamama, 2005). In general, cooking time for tepary bean may be longer than that of common bean (Small, 2014), but considerable variability for seed composition and cooking traits exists among tepary bean genotypes (Porch *et al*., 2017). Tepary bean accessions with fast cooking times include T30547 and Neb-t-1s (Porch *et al*., 2017). These accessions are light-coloured, with higher elemental composition in magnesium, copper, nickel, cobalt, potassium, and iron. The short cooking time promotes convenience, and allows for energy saving amidst intermittent power supply and high fuel costs commonly found in sub-Saharan Africa. The genetic differences with respect to seed composition and cooking traits can be harnessed and utilized for crop improvement.

Tepary bean seeds contain flavonoids and phenols, which are associated with antioxidant activities (Salas-López *et al*., 2018). The flavonoids in tepary bean have been reported to have anti-cancer properties (Salas-López *et al*., 2018). Further, tepary beans have high levels of lectin protein, which inhibits the proliferation of colon cancer (Moreno-Celis *et al*., 2020) and may have anti-diabetic effects (López-Ibarra *et al*., 2021). While lectins such as phytohemagglutinins have some toxicity when raw, typical cooking practices reduce content of these compounds to trace or undetectable levels (Shimelis and Rakshit, 2007).

7. USAGE

Tepary bean is mostly cultivated for its mature nutrient dense dry seeds, which are cooked using a variety of methods, particularly by boiling, but occasionally also by steaming, frying, or baking (Rana and Jatav, 2017).

Tepary bean has also been used as a short-duration forage crop for livestock in arid regions (Bhardwaj, 2013). Tepary bean forage yields are comparable to alfalfa, and their nutritional quality are comparable to alfalfa hay, perennial peanut hay, and soybean (Bhardwaj, 2013). The forage is comprised of 21.4% protein, 37.5% acid detergent fibre, 41.1% neutral detergent fibre, 60.8% total digestible nutrients, and 1.12% fat (Bhardwaj, 2013).

8. GENETIC RESOURCES

Table 1: Gene banks and other selected institutions maintaining tepary bean genetic resources Globally, a number of institutions are involved in the maintenance and *ex situ* conservation of tepary bean genetic resources.

Institution	Number of var. *tenuifolius/ parvifolius* (=*montanus*)	Number of var. *acutifolius*	Source
USDA- The Western Regional Plant Introduction Station, Pullman, WA	25	536	GRIN NPGS 2025, https://npgsweb.ars-grin.gov/gringlobal/search.aspx
CIAT-Colombia and backup at Svalbard Global Seed Vault in Norway	20	326	Genesys PGR 2025, https://www.genesys-pgr.org/
Virginia State University, USA		200	Prof. Harbans L. Bhardwaj
The National Plant Genetic Resource Centre of Botswana		35	Dr. Odirileng O. Molosiwa
CIAT- Malawi		20	Dr. Wilson Nkhata
University of KwaZulu Natal		50	Prof. Hussein Shimelis

9. CHARACTERIZATION OF DIVERSITY

Tepary bean has been characterized using phenotypic traits as well as molecular markers. The information on phenotypic characterization is provided in Table 2.

Table 2: Summary of selected tepary bean phenotypic characterization experiments.

Evaluated accessions	Key traits	Study location	Source
G40068, G40159, CMT 38, CMT 109, CMT 187	Pod biomass, pod number, HSW, seed number at high temperatures and drought	Colombia	(Muñoz *et al*., 2021a); Muñoz *et al*., 2021b)
10006, 10017, 10020, 10011	Water potential, chlorophyll fluorescence, soluble sugars	Mexico	(Leal-Delgado *et al*., 2019)
G40271, G40019, G40006, G40230, G40012, G40129, G40222, G40226, G40253A, G40221, G40258A, G40193, G40224, G40197, G40220, G40253, G40261, G40254, G40256, G40248, G40210, G40195A, G40181, G40289, G40194)	morpho-phenological, agronomic and physiological traits	Colombia	(Mohamed *et al*., 2005)
T30387 to T30567 (27 breeding lines), TARS-Tep 8, 10, 22, 23, 32, Neb-T-1s.	Seed composition, cooking time, soluble sugars, yield, HSW, HI, biomass	Puerto Rico, USA	(Porch *et al.*, 2017)
TARS-Tep 23 (PI 502217-s/PI 440799)	Broad abiotic stress tolerance and rust and common bacterial blight resistance	Puerto Rico and California USA, Colombia, and Honduras	(Porch *et al*., 2021)
G40159, G40068	LAI, biomass production, PPI, PHI, seed yield, leaf chlorophyll content, SBR, PPE, SPE, stem biomass, HI, HSW	Palmira, Colombia	(Rao *et al.*, 2013)
TB6, TB11, TB17, TB27, PI 196932, PI 197401,PI 200902, PI 312198, PI 321637, PI 440798, PI 440801, PI 440804	Photosynthetic efficiency (Fv/Fm)	Virginia, USA	(Bhardwaj, 2015)

Evaluated accessions	Key traits	Study location	Source
TBGH4, TBGH7, TBGH8, TBGH10, TBGH15, TBGH18, TBGH29, TBGH31	Photosynthetic efficiency (Fv/Fm), RI, RWC, biomass, TE	Virginia, USA	(Narina *et al*., 2014)
Neb-T-l-s, Neb-T-6-s, Neb-T-Sa-s, Neb-T-15-s, GN-605-s, GN-610-s, PIs 321637-s, 321638-s, 440788-s, 440806-s, and 502217-s	HSW and seed yield	Puerto Rico, USA	(Miklas *et al*., 1994)
Sonoran Gold, Tepary Gray, Tepary White, G40001	Seed yield and HI	Saskatchewan, Canada, and Puerto Rico, USA	(Souter *et al*., 2017)
PI 321638	RWC, GS, LP, Proline, enzymatic activity	Turkey	(Türkan *et al*., 2005)
Tepary negro, Tepary Café	Root length	Mexico	(Galindo *et al*., 2018)
NE # 19, NE # 8A, NE # 5, NE #7	Dry matter accumulation & partitioning, seed yield, CF, TR, gs, LA, RWC, RD, SDM, LDM, RDM, RM	Assiut, Egypt	(Mohamed *et al*., 2005)
MN 258/78	Leaf area, leaf dry weight, stem dry weight, root dry weight, total plant dry weight, stomata resistance, root depth, water and osmotic potential	Minnesota, USA	(Markhart, 1985)
TARS-Tep 32	Shoot biomass, photosynthesis traits, stomatal density and size, transpiration efficiency, WUE	Mexico	(Polania *et al*., 2022)
Neb-T-1-s, Neb-T-6-s, Neb-T-8a-s, NebT-15-s, GN-605-s, GN-610-s, PIs 321637-s, 321638-s, 440788-s, 440806-s, 502217-s, and PI 312122-s	Bean Golden Mosaic Virus	Puerto Rico, USA and Honduras	(Miklas and Santiago, 1996)
Tepary Diversity Panel (422 lines total, various subsets)	Seed colour, seed area, fusarium rating, weevil rating, CBB rating,	Puerto Rico, USA, and Colorado, USA	Bornowski *et al*. 2023
Main panel: 22 varieties	Seed yield (in heat stress, drought, and control conditions), seed size, seed colour	California, USA, Nebraska, USA, and Colombia	Barrera *et al.*, 2024

Evaluated accessions	Key traits	Study location	Source
Tepary bean diversity panel: 45 lines	Seed yield and yield related traits under non-stress and drought stress conditions	Kasinthula and Bunda, Malawi, Ukulinga, Pietermaritzburg, South Africa	Mwale *et al*., 2024
USDA Fortuna (CV-352, PI 698459), TARS-Tep 90, TARS-Tep 22, Sacaton white, G40001	Seed yield, seed size, seed quality, tolerance to *Bean golden yellow mosaic virus*, leafhopper, CBB, powdery mildew, and rust resistance	Puerto Rico, Haiti, Dominican Republic, Honduras, Costa Rica	Porch *et al.*, 2023

Abbreviations: CBB, common bacterial blight; CF, Chlorophyll fluorescence; gs, Stomatal conductance; HI, Harvest index; HSW, Hundred seed weight; LA, Leaf area; LAI, Leaf area index; LDM, Leaf dry mass; PHI, Pod harvest index; PPE, Pod production efficiency; PPI, Pod partitioning index; RD, Root depth; RDM, Root dry mass; RI, Relative injury; RWC, Relative water content; SBR, Stem biomass reduction; SDM, Shoot dry mass; TE, Transpiration efficiency; TR, Transpiration rate; LP, Leaf potential.

For genetic diversity assessment, common bean-derived single nucleotide polymorphism (SNP), amplified fragment length polymorphism (AFLP), and simple sequence repeats (SSR) markers have been utilized in tepary bean for genetic diversity assessment (Gujaria-Verma *et al*., 2016; Blair *et al*., 2012; Parker and Gepts, 2021; Muñoz *et al*., 2004; Blair *et al*., 2006). Like many crops, there has been a strong trend towards the use of SNP-based technologies for genetic diversity analyses over recent years (e.g., Bornowski *et al*., 2024).

10. BREEDING OBJECTIVES

Generally, breeding in tepary beans has focused on the improvement of abiotic and biotic stress tolerance, of seed yield and related trade, nutritional content, and of market class traits, particularly cooking time. Recently, there has been a renewed interest in tepary bean breeding with a special focus on interspecific improvement of common bean for stress tolerance using tepary bean genetic resources.

10.1 Breeding for improvement in seed yield and associated traits

Seed yield is a quantitative trait that is strongly influenced by the environment. Tepary bean landraces with high yields across variable environments include G40068 and G40173A (Parker *et al*., 2024; Barrera *et al.*, 2024).

The first modern selection and breeding strictly within *Phaseolus acutifolius* was conducted by USDA-ARS in Mayaguez, Puerto Rico. These projects have improved several traits simultaneously, including high yield under high temperatures and drought, resistance to common bacterial blight and weevils, large seed size, and improved plant architecture. This program resulted in the release of the lines TARS-Tep 22 and TARS-Tep 23 and the cultivar USDA Fortuna, all of which are derived from crosses between landraces; as well as TARS-Tep 32, derived from a single plant selection from a landrace (Porch *et al*., 2013, 2021, 2024). These accessions have multiple disease resistances, yield potentials up to approximately 3,500 kg/ha, and perform best under high temperature and low moisture conditions.

High to moderate and significant correlations between seed yield, number of pods per plant (Kuruvadi and Valdez, 1993), plant height, stem biomass, number of viable seeds per plant, number of seeds per pod, hundred seed weight, length and width of pods (Suárez *et al.*, 2022) have been reported, indicating that simultaneous selection for these traits could potentially accelerate yield gains. To maximize yield gains and sustainable breeding progress, yield-trait associations should be complemented with more varietal testing and more replications across different environments, including those with high abiotic and biotic stress pressure.

10.2 Breeding for abiotic stress tolerance

Several studies have assessed the abiotic stress tolerance levels of diverse tepary bean germplasm, including in drought, heat, saline, and low-temperature environments (Souter *et al*., 2017). Drought stress factors (climatic and edaphic) limit bean productivity in tropical and subtropical countries (Rao, 2014). However, studies have revealed that tepary bean is relatively more tolerant to drought than common bean (Parker *et al*., 2024; Barrera *et al*., 2024). Physiological and morphological mechanisms including stomatal adjustments, small leaf structure, and deep rooting allow for efficient water-use and drought-adaptation of the crop (Mohamed *et al*., 2005; Beebe *et al*., 2013). Tepary bean phenotypic characterization information is presented in Table 2. Tepary bean sources of drought tolerance have been identified and include TARS-Tep 22, TARS-Tep 32 (Porch *et al*., 2013), G40068, G40159 (Beebe *et al*., 2013), NE # 5, and NE # 19 (Mohamed *et al*., 2005; Mohamed *et al*., 2002). Heat stress, manifested by high temperatures of more than 30°C during the day and/or more than 20°C at night, reduces common bean yield significantly, in part due to decreased pollen fertility (Assefa *et al*., 2019). Tepary bean is native to regions with temperatures greatly exceeding this (Fig. 2), and is far better suited at handling temperatures above this range (Small, 2014). Greater pollen viability (Muñoz *et al*., 2006) and dehydration avoidance (Mohamed *et al*., 2002) have been reported as underlining mechanisms for higher heat tolerance in tepary beans, while stomatal control is less likely (Medina *et al*., 2017; Buckley *et al*., 2025). Breeders have identified tepary bean genetic resources that are particularly tolerant to heat, such as TARS-Tep 23 (Porch *et al*., 2021), TARS-Tep 22, TARS-Tep 32 (Porch *et al*., 2013), PI 200902, PI 440785, PI 440789 (Rainey and Griffiths, 2005), GN-605-s and GN-610-s (Miklas *et al*., 1994), while the wild genotypes PI 219445 and W6 15578 are relatively tolerant of cold, and this tolerance has been transferred to the common bean gene pool (Souter *et al*., 2017). Furthermore, salinity-tolerant tepary beans have been identified, including UN ACC1, UN ACC2 (Goertz and Coons, 1991), G40148, G40022, G40142, and G40110 (Bayuelo-Jiménez *et al*., 2002).

10.3 Breeding for resistance to biotic stresses

A variety of pathogens, including bacteria, fungi, viruses, and parasitic nematodes, reduce bean yield significantly. Studies screening for resistance to diseases and pests in tepary bean have been conducted (Table 2). The sources of resistance to common bacterial blight (CBB), caused by *Xanthomonas campestris* pv. *phaseoli* (Smith) Dye, (Xcp), include PI 440795 (Shi *et al*., 2012), G40029, G40156 (Singh and Muñoz, 1999), G40057, G40150, G40122, G40224, G40010 (Vargas *et al*., 2014), TARS-TEP-22, TARS-TEP-32, (Porch *et al*., 2013), and many others, and this resistance has been successfully transferred to the common bean gene pool (Singh and Muñoz, 1999; Michaels *et al*., 2006). Sources of resistance to Fusarium wilt disease include Neb-T-5-s (Miklas *et al*., 1998), PI 310800, PI 312122, PI 319442, PI 440803, PI 200749, PI 209840, PI 331181, PI 458873, and PI 458874 (Salgado *et al*., 1994). TARS-Tep 22 and TARS-Tep 23 have immunity to rust (Barrera-Lemus, 2021). Resistance to potyviruses such as bean common mosaic virus (BCMV) and bean common mosaic necrosis virus (BCMNV) are generally lacking in tepary bean compared to common bean. Despite this, there is evidence that some level of resistance can be found in the accessions G40041, G40042, G00044, G40177E and G40177E1 (Vargas *et al*., 2014). The strongest resistance is found in wild accessions, rather than in cultivated materials (Bornowski *et al*., 2023), suggesting opportunities for tepary improvement. G40023, G40043, G40063, G40159, G40138 (Salgado *et al*., 1994), PI 502217 and Neb-T-6-s (Rainey and Griffiths, 2005), TARS-Tep 22 (Porch *et al*., 2013), TARS-TEP 23 (Porch *et al*., 2021), and USDA Fortuna (Porch *et al*., 2024) are examples of tepary bean accessions with multiple resistances to diseases such as Fusarium wilt, ashy stem blight, common bacterial blight, bean rust, and powdery mildew.

11. BREEDING METHODS

11.1 Hybridization and conventional breeding

The extreme abiotic and biotic resistances of tepary bean make it an important source of genetic variation for the improvement of other species, particularly common bean. Successful fertile crosses between wild and cultivated tepary bean genotypes have been performed (Blair *et al*., 2003). Interspecific hybridization of tepary bean with common bean has historically required embryo rescue and use of common bean as a pistillate parent for viable offspring production (Honma, 1956; Mejía-Jiménez *et al*., 1994). Tepary bean genes for biotic (common bacterial blight) and abiotic (drought) stress resistance and/or tolerance have been successfully introgressed into common bean (Thomas and Waines, 1984; Parker, 1985; Kusolwa *et al*., 2016; Souter *et al*., 2017). For instance, tepary bean was the source of resistance to common bacterial blight found in the VAX lines (Singh and Muñoz, 1999) and OAC Rex (Michaels *et al*., 2006). Similarly, a released red kidney common bean line AO-1012-29-3-3A with bean weevil resistance was developed from an introgression of lectin protein from a tepary bean line, G40199 (Kusolwa and Myers, 2011; Kusolwa *et al*., 2016). This has subsequently been moved broadly into common bean (Chinji *et al*., 2024).

Recently, the need for embryo rescue was overcome through the development of interspecific hybrid bridge lines. These, called VAP lines due to their ancestry, are derived from crosses between *Phaseolus vulgaris, P. acutifolius,* and *P. parvifolius* (=*P. montanus*). These enhance crossability between common bean and tepary bean and eliminate the need for embryo rescue (Barrera, 2022; Barrera *et al*., 2018), which could revolutionize the accessibility of tepary genetic diversity for common bean breeding and *vice versa*.

11.2 Marker-assisted selection and genetic control of traits

The use of marker-assisted selection in tepary bean is currently extremely limited, but genetic and genomic resources for the species are growing (e.g., Moghaddam *et al*., 2021; Bornowski *et al*., 2023; Mwale *et al*., 2023; Ravelombola *et al*., 2024). Limited studies have reported the mechanisms controlling the inheritance of genes for key traits such as seed yield and pest and disease resistance in tepary beans. Tepary bean crosses were performed between a cultivated tepary bean from Arizona; G40022 and two wild tepary bean accessions, namely: G40186, a wild *P. parvifolius* from Jalapa in Mexico; and G40240, a wild *P. acutifolius* var.

tenuifolius from Durango, Mexico. Flower and stem colour were controlled by few genes and followed simple Mendelian inheritance, whereas plant height, flowering date, maturation date, leaf size, leaf colour, pod size, yield and yield components were controlled by multiple genes (Blair *et al*., 2003). Bornowski *et al*. (2023) genetically mapped seed colour, seed area, and resistances to CBB, fusarium, BCMV, weevils using a novel Tepary Diversity Panel of 422 lines. These resources could be vital for future selection within the tepary bean gene pool, as well as moving this variation between species.

11.3 Mutagenesis

Mutagenesis through ethyl methane sulfonate (EMS) treatment has been utilized to widen the genetic diversity of cultivated tepary beans for heat and drought tolerance (Muñoz *et al*., 2021b). About 400 mutant lines have been developed through EMS treatment from two tepary accessions, namely, G40068 and G40159, with the aim of identifying those with improved abiotic stress tolerance (Muñoz *et al*., 2021b).

11.4 Potential biotechnological intervention

Tepary bean is unique among *Phaseolus* species in being fairly simple to transform genetically. A series of transgenic studies have identified increasingly reproducible methods with which to introduce novel genetic variation into *Phaseolus* from the quaternary gene pool of the genus (Dillen *et al*., 1997; De clercq *et al*., 2002; Zambre *et al*., 2005). This gives tepary bean potential as a research system for *Phaseolus* genetics broadly, and the species could be used to introduce transgenes into other species. Genetic manipulation of tepary beans using *Agrobacterium tumefaciens* has also led to the secretion of pharmaceutically-valuable bioactive lectins which lead to cancer cell death. The compounds are expressed through roots in a process called rhizosecretion, and can be readily harvested from hydroponically-grown plants (Martínez-Alarcón *et al*., 2019).

Common bean and tepary bean each display important and complementary benefits. Ultimately, the greatest gains for breeding and research in each species would likely be achieved through hybridization with the other. Historically, this has required embryo rescue, which is relatively costly and time-consuming. Hybrid bridge lines, which can be crossed readily with either gene pool, have recently been developed through congruency backcrossing (Barrera, 2022; Barrera *et al*., 2018). These are tremendously valuable for exchanging the optimal traits from each species. Extensive genotyping has been conducted on the bridge lines, providing evidence on the genetic cause of this variation (Barrera *et al*., 2022). These have been developed into interspecific populations, which are undergoing extensive phenotypic and genotypic evaluation (Cruz *et al*., 2023; López-Hernández *et al*., 2023).

Production of varieties desired by consumers in many regions is threatened by climate change, and would greatly benefit from approaches that can promote crop resilience at low cost. Ultimately, maximizing tepary bean's beneficial effects on human health and well-being will require a strong and proactive combination of breeding, bio-diversification, and field management strategies.

12. AGRONOMY

Tepary bean can be grown in a wide range of environments and habitats, including alluvial soils, and is fairly tolerant to alkalinity and salinity. Well-drained and sandy soils are preferred, while it is not adapted to heavy clay (Small, 2014). In cultivated environments, a sowing depth of 3-4 cm and an intra-row spacing of 10 cm has been recommended (Tohono O'odham Community Action, 2010; Molosiwa *et al*., 2022).

Tepary beans fix nitrogen through symbiotic relationships with *Rhizobia* and *Bradyrhizobia* bacteria, improving their suitability for low-input agricultural systems. The crop's ability to fix nitrogen reduces the need for application of synthetic inorganic nitrogen fertilizers as well as safeguards the aqueous ecosystems from pollution due to run-off. Studies on tepary bean and *Bradyrhizobium* strain interaction have revealed that *Phaseolus* Spec. #3, UMR-3255, and UMR-3043 were efficient in tepary bean nodulation (Mohrmann *et al*., 2017). Intercropping tepary beans with maize was reported to be disadvantageous to both crops under semi-arid conditions in Kenya (Shisanya, 2003), this happens due to decrease nutrient scavenging and light interception. Inoculation of tepary bean with *Rhizobium* strain R3254 improved the seed yield of tepary significantly more than other strains in a tepary-maize intercrop (Shisanya, 2003).

Tepary beans are resistant to numerous pests (such as bean weevil, leafhopper, and thrips) and diseases (such as common bacterial blight, Fusarium wilt, angular leaf spot, and ashy stem blight) (Singh and Muñoz, 1999; Salgado *et al*., 1994; Miklas *et al*., 1998; Porch *et al*., 2013). Days to flowering and harvest vary depending on the variety and environment, but range from 27 to 40 days to flowering and 60 to 120 days to maturity. Harvesting and threshing may be done manually or mechanically through cutting, windrowing, and combining.

13. SUMMARY OF ESSENTIAL FEATURES OF TEPARY BEANS

Tepary bean plants possess unique features that make them an ideal crop to meet grower and consumer needs. The following are some of these essential features:

- Tepary bean plants maintain productivity under harsh environmental conditions such as drought, heat, and saline soil. This makes it an ideal crop for cultivation in arid and semi-arid regions of the world where climate change effects are prominent.
- Tepary bean is resistant to numerous pests and diseases. These natural resistances offer the opportunity to apply fewer pesticides, hence ensuring ecological sustainability.
- Tepary bean grows in poor soils with low soil fertility.
- Tepary bean grains are rich in protein, fibre, and essential mineral elements. This makes the species an essential tool to meet nutritional needs among consumers around the world.
- Tepary beans require low levels of farm inputs. This makes them an affordable crop for subsistence farmers in sub-Saharan Africa who have limited economic purchasing power.
- The nitrogen fixation ability of tepary beans makes them a sustainable component in farming systems.
- Tepary bean forage is highly nutritious and can serve as a feed for livestock.
- Tepary bean has useful abiotic and biotic stress tolerance genes for common bean improvement.
- Tepary bean grains are a source of lectins, which are important for the prevention of non-communicable diseases such as cancer and diabetes.

14. CURRENT RESEARCH PRIORITIES

A number of research focal areas should be emphasized for improving breeding progress in tepary beans, among which include:

- Continued hybridization between common bean and tepary bean to transfer the best qualities of each species and pyramid them into a single package.
- Broadening the genetic base of cultivated tepary beans using wild or other sources.
- Continued use and development of bridge lines to facilitate movement of useful genetic variation between common bean and tepary bean.
- Intensive programs of crossing and selection, to maximize yield under high biotic and abiotic stress and to improve culinary quality.
- Development of tepary bean genomic tools to facilitate marker-assisted selection and breeding.
- Improvement of tepary bean seed size and cooking time characteristics for wide adoption.
- To determine the mode of gene action governing the inheritance of key traits in tepary bean to guide breeding strategies to adopt in breeding programs.
- Identify and characterize the sources of aluminium toxicity tolerance.
- Breeding for enhanced micronutrient content and utilization in tepary bean.
- Breeding for enhanced biological N fixation using *Rhizobium* species and efficient use of soil P.
- An improved understanding of consumer preferences regarding tepary bean and other pulses.

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