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Andean Lima Bean Ecology and Its Potential Contribution to Food Security

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ABSTRACT

The Andean lima bean (ALB) (*Phaseolus lunatus* L.), also known as "Pallar" in Peru, is a large, semi-flat, kidney-shaped rarely investigated legume. This ancestral legume lacks in-depth scientific reports and is mainly cultivated in the coastal region of the Ica valley. Its consumption dates back to ancient times, as evidenced by archaeological finds from pre-Columbian civilizations in Peru, and it is still part of the Peruvian diet today. ALB has been domesticated and adapted to climate change in arid territories and under peculiar agronomic conditions in Peru, making the crop tolerant to various stresses, including drought. Like the common bean, ALB is an important source of protein, carbohydrates, dietary fiber, and micronutrients that are essential for a nutritious diet. However, the information on its diversity, particularly the native varieties that are the ancestors of the commercial lima bean "Pallar de Ica," is scarce. Therefore, this review consisted of synthesizing and analyzing important aspects of the little known ALB, such as its morphological description, domestication, response to climate change, nutritional composition, and relevance to food security and potential for cultivation to address food shortages.

1 | Introduction

The Andean lima bean (ALB) (*Phaseolus lunatus* L.), a member of the Leguminosae family, is a sustainable source of protein that has been part of the traditional diet in many parts of the world for thousands of years. In addition, its great economic potential, which is increasingly recognized, makes it a viable option for improving the environmental sustainability of crops (Keskin et al. 2022; Lewis and Schrire 2003; Semba et al. 2021). The classification of *P. lunatus* L. has been thoroughly studied, and two distinct gene pools have been identified: wild and domesticated. Fofana et al. (1999) stated that cultivated varieties (*P. lunatus* var. *lunatus*) have been divided into three groups, each with unique seed characteristics and growing regions: Cv-gr: sieva, Cv-gr: potato, and Cv-gr: Big Lima (Baudet 1977). One of ALB varieties is "Pallar," an improved unpigmented variety of big Lima, whose name comes from the ancient Peruvian Quechua language and is derived from the term "Paxllec" of the Mochica culture (Eloranta 2019). "Pallar" is a native legume that has been consumed along the Peruvian coast for centuries (Rodríguez et al. 2023).

Subsequent research has shown that the Moche culture of Peru was one of the first to consume and trade "Pallar" before the Spanish conquest of Peru in the 16th century (Ferreira and Dargent-Chamot 2002). In the iconography of the Moche culture, the "Pallar" is represented in scenes of hunting, fighting, and play. The Moche also managed it as a widespread crop, because its cultivation required short periods of irrigation and, in tropical conditions, they could obtain up to four harvests per year. In fact, the "Pallar" crop became more important than maize (Cueva 2018; Hacquenghem 1984; Rodríguez et al. 2023). During the viceroyalty of Peru, after the arrival of European explorers in the Americas, "Pallar" was exported to the rest of America and

Europe in boxes marked "Lima, Peru," which is why it is known as "lima bean" in English-speaking countries (Baudoin 1993; Esquivel, Castiñeiras, and Hammer 1990). Figure 1 shows the location of the most representative pre-Hispanic cultures on the coast of Peru, whose vestiges of seeds and iconography in ceramics and textiles are evidence of the presence and importance of this crop. The Mochica culture stands out in the north and the Nazca, Paracas and Ica cultures in the south. The pallares cultivated in the region of Ica are ALB have a denomination of origin granted in 2007 and are distinguished by their sweet taste due to the low level of hydrocyanic acid, thin shell, easy and quick cooking and smooth and creamy texture. It is noteworthy that they come from the ancestral pigmented ALBs domesticated by the Mochica culture in northern Peru, also known as "pallar mochero", which stand out for their black and cream pigmentation. Unfortunately, some of these ancestral varieties are on the verge of extinction.

The world production of lima bean is difficult to assess. Many countries and the Food and Agriculture Organization of the United Nations (FAO) do not keep separate statistics on lima bean production. FAO legume crop reports group lima bean with eight other species of the genera *Phaseolus* and *Vigna*, which are collectively classified as dry beans (Ernest and Wisser 2024). In Peru, it is marketed as a fresh legume in pods and as a dry bean for human consumption, as it is rich in protein and other nutrients beneficial to human nutrition (Sandoval-Peraza et al. 2020).

In 2022, Peru exported 9.9 million kilograms of Pallar valued at US$16.4 million. The main export destinations were the United States, Japan, Spain, Lebanon, Jamaica, Canada and other countries with smaller quantities (Agrodata, 2024). The geographic distribution is concentrated in the coastal regions (Ancash, Lima, and Ica), as production areas, and in some upland departments (Junín, Ayacucho, Huancavelica, Apurímac, and Puno), with little or no significant production (Rodríguez et al. 2023). The consumption of this legume was 8 kg/inhab/year in 1984 but decreased to 5.3 kg/inhab/year in 1990. It should be noted that by 2021, the consumption of legumes in the country had increased to 7.5 kg/inhab/year, which is lower than the 9 kg/inhab/year recommended by the World Health Organization (AGRARIA. PE, 2021; Rodríguez et al. 2023).

Currently in the Ica region there are 12 native varieties recognised with Designation of Origin under the name "Pallar de Ica" (INDECOPI, 2017). It is also important to note that the cultivation of "Pallar" takes place during the period between February and April, while the harvest is carried out in the Peruvian coast between August and October (Espinoza et al. 2022). Thanks to the favorable agroecological conditions in this region, there is a high potential to significantly increase production in a profitable way. "Pallar is characterised by its large size, white colour, pleasant taste and nutritional benefits in terms of lysine as limiting amino acid. (Ccala Sucasaca and Ramirez Carrasco 2021). Although pulses are rich in protein with a high lysine content, they are deficient in cysteine and methionine, which are usually present in significant amounts in cereals. Therefore, diets that combine cereals and legumes achieve a better balance and supplementation of limiting amino acids, thus improving the quality of proteins in the diet of people who do not have access to animal protein (Juliano 1999).

FIGURE 1 | History and geographical distribution of the main pre-Hispanic cultures of the coast of Peru where ALB (*Phaseolus lunatus L.*) cultivation has been found. (a) Iconography of the Mochica culture showing ALB. (b) Iconography of the domestication of ALB cultivation in Ica and Paracas. (c) Areas producing domesticated Pallar in the southern area of Ica. (d) Designation of origin 'Pallar de Ica'.

In this context, the aim of our review is to deal specifically with the ecology of the ALB, with a special focus on the type of lima bean known as "Peruvian big Lima." The review provides an overview of phylogenetics, archaeology, ecophysiology, high temperature tolerance, soil adaptation, water stress, biological nitrogen fixation, and food security. These specific aspects are examined in detail in this review, responding to the need to better understand the ecology of the ALB and its potential contribution to food security.

2 | Phylogenetics and Archaeology of *P. lunatus* L. of the Andes

In his classic *Origin of Cultivated Plants*, de Candolle (1883) emphasized that the cultivated forms of the bean did not originate in the Old World, as previously thought, but in the New World. Subsequently, the genus *Phaseolus* has been extensively studied to elucidate its origins, evolutionary pathways, and genetic diversity (Baudet 1977). These studies have emphasized the importance of vernacular names in native languages for describing and classifying numerous bean varieties worldwide, highlighting the importance of linguistic diversity in understanding the history and evolution of this plant (de Candolle 1883). The common bean and lima bean are thought to have originated in the Americas, and efforts have been made to understand how *Phaseolus vulgaris* and *P. lunatus* L. underwent two independent domestications: one in Mesoamerica and the other in the Andes (Bitocchi et al. 2017).

Extensive research has revealed the presence of three significant genetic pools within the *Phaseolus* species—two Mesoamerican genetic pools (MI and MII) and one Andean genetic pool (AI)—all of which consist of wild and domesticated lima bean species (Andueza-Noh et al. 2013; Chacón-Sánchez et al. 2021; Martínez-Castillo et al. 2016). The MI genetic stock is distributed primarily in the tropical dry forests of the Pacific coastal plain of Mexico at an average elevation of ~450 m, with a small group of accessions on the western side of the Neovolcanic Axis at higher elevations (1.250–1.810 m.a.s.l.). The MII genetic pool is present in the lowlands of Mexico (~550 m.a.s.l.) along the Atlantic coast (Gulf of Mexico) and the Yucatan Peninsula, as well as to the southeast of the Isthmus of Tehuantepec, the Caribbean, and South America (Bitocchi et al. 2017; Chacón-Sánchez and Martínez-Castillo 2017).

The AI gene pool is restricted from southern Ecuador to northern Peru, where these species actually originated (Bitocchi et al. 2017; Chacón-Sánchez and Martínez-Castillo 2017; Garcia et al. 2021). The studies of Serrano-Serrano et al. (2010) support the origin of the wild ALB, followed by an early divergence due to geographic isolation associated with the uplift of the Andes and the closure of the Isthmus of Panama. This hypothesis is supported by studies conducted by Andueza-Noh et al. (2013); in their study, a total of 262 wild specimens and domesticated accessions were analyzed, of which 235 belonged to the Mesoamerican gene pool and 27 to the Andean gene pool. Through sequence analysis of the chloroplast spacers trnL-trnF and atpB-rbcL, it was determined that the AI group is distributed exclusively in South America, mainly between Ecuador and Peru, although it is also observed less frequently in Colombia, Bolivia, and Argentina, at altitudes ranging from 6 to 2620 m.a.s.l.

These results support the possibility that domestication of wild Andean lima beans occurred in the south-central region of Peru. In addition, the existence of another Andean gene pool (AII) has been reported in the central Andes of Colombia (Caicedo et al. 1999), which determined the genetic relationships and phylogeny based on genome-wide DNA analysis using restriction fragment length polymorphisms (RFLPs) of Andean beans. These results are significant because they support the south–north dispersal of the species to other parts of the Andes. Studies on the diversity of lima bean cultivars have mainly been conducted using samples collected in Central America and Mexico. However, studies on ALB in South America remain scarce (da Silva et al. 2015; Fofana et al. 1999).

The presence of domesticated *P. lunatus* dates to about 5600 ^{14}C year BP (about 6400 cal BP) in the valleys of Chilca, on the southern coast of Peru. On the other hand, the antiquity of common beans in the central highlands of Peru has been reported as early as 4600 ^{14}C year BP (*ca.* 5000 cal BP) (Kaplan and Lynch 1999). Additional studies of *P. lunatus* starch found in human teeth from the preceramic culture of Ñanchoc in Peru provide pertinent information on the age of the lima bean, which was found in a sample dated to 6970 ^{14}C year BP (*ca.* 5000 cal BP). However, the similarity of the starch of *P. lunatus* or *P. vulgaris* suggests that the unique domestications of the Andean lima and common bean occurred in southern Ecuador/northern Peru and southern Peru/Bolivia, respectively (Piperno and Dillehay 2008).

3 | Ecophysiology of ALB (*P. lunatus* L.)

The ALB-type "Pallar" is a diploid (2n = 22) herbaceous species with a determinate growth pattern and erect plants or an indeterminate growth pattern with staggered budding and inflorescence. The plant is mainly creeping and can be annual, biennial, or perennial (regrows when watered). Its stems are herbaceous, some of which are woody, ribbed, slightly hairy, or glabrous. Its leaves are alternate, trifoliate, with pointed tip and rounded base, and are dark green, with or without hairs (IPGRI, 2001).

The legume family is one of the main food resources for pollinators and is mainly pollinated by bees. Legumes and bees have been associated with each other throughout their evolutionary histories and this association reaches its climax in the subfamily Papilionoideae (Leppik 1966). The pollination of plants generally occurs by indiscriminate mating, either by wind dispersal of pollen or by random visits of pollinating insects attracted to the flowers (Shivanna and Tandon 2014). This phenomenon also applies to highly heterozygous bisexual animals, where the resulting chaotic segregation tends to lead to a gradual improvement in the breeding of such species. Pallar flower colour may vary according to cultivar type, e.g. pallars of determinate and indeterminate growth pattern have white flowers and others of non-indeterminate growth pattern have light pink, violet or purple flowers (Allard 1999; Espinoza et al. 2022) (Figure 2).

The evolution of ALB in South America, through its adaptation to regional environmental and eco-physiological conditions, has

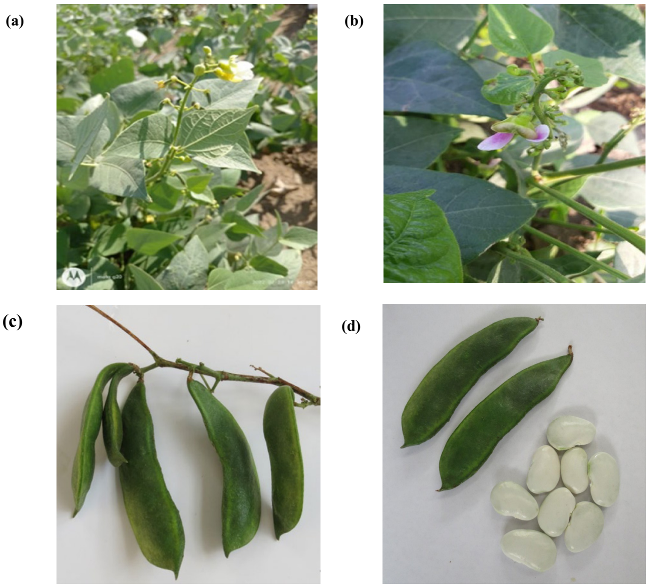

FIGURE 2 | Pallar of Ica (*Phaseolus lunatus* L). (a) "Pallar" plant. (b) White flower. (c) Fresh pods. (d) Fresh "Pallar" seeds.

involved changes in landraces. In a study that included 36 local accessions of *P. lunatus* L. in Colombia (Quilichao, Palmira, Paita, and Monteria) grown for 2 years in four different locations, Lyman (1983) showed the existence of significant interactions between genotypes and environmental conditions such as temperature, humidity, and soils, which are relevant for the improvement of important agro-morphological traits. The information on the botanical and adaptive characteristics of grain legumes in the tropical lowlands can be summarized in a table, adapted from the work of Wall (1973) to facilitate comparison of their potential in specific situations. Species have been grouped according to their ecological use patterns, although overlaps in adaptation and macroclimates are found within the same region (Table 1).

3.1 | Tolerance of ALB (*Phaseolus lunatus* L.) to High Temperatures

The main effects of high temperatures on plants (usually around 30 °C) include reduction of life cycles, pollen abortion, bean shrinkage, reduction of seed reserves, anther indehiscence, and reduction of pollen tube development (Paredes-López, Reguera, and Octavio 2023). Lima bean, according to its distribution in the wild, is adapted to tropical lowland savanna climatic conditions. Over the years, ALB has evolved and adapted to different climates, from humid, dry, or semi-arid tropics and temperate regions (Duke 1981; Temegne et al. 2021). Ideal temperatures for growth range from 16 °C to 27 °C (Baudoin 1993). Some varieties may have difficulty in germinating if soil temperatures are below 20 °C, and germination is optimal in the range of 21 to 27 °C (Duke 1981). A recent study conducted by Machado et al. (2022) in Brazil characterized 46 *P. lunatus* L. accessions from various countries. The accessions were planted in pots and evaluated for high temperature conditions, morphology, and phenology. The results showed that accessions from Azerbaijan, Philippines, United States, Brazil, and Peru had lower values for days to flowering initiation and average number of days to maturity. The mean values ranged from 37 to 51 days and 62 to 91 days, respectively. It should be noted that these values represent a general trend and variations may occur depending on the specific conditions of each plant and its environment. In addition, it presented higher values for the average number of flowers emitted and pods formed, in contrast to lower values for the average number of aborted pods. The group's accessions displayed average measurements for pod length, width, and thickness, as well as seed length, width, and thickness. The mean values ranged from 49.9 to 66.84 mm for pod length, 13.4 to 17.17 mm for pod width, 6.4 to 8.3 mm for pod thickness, 10.75 to 14.54 mm for seed length, 7.78 to 9.8 mm for seed width, and 3.84 to 4.69 mm for seed thickness. Additionally, they thrive in temperatures ranging from 20 to 30°C, with optimal temperatures around 30 to 35 °C. Based on the results, these species demonstrate significant potential for future breeding programs due to their early maturation and high yield. On the other hand, Ernest and Wisser (2024) evaluated data from 8 years of testing of lima bean genotypes from the United States planted annually to understand the cause of yield loss due to heat stress in lima bean (*P. lunatus* L.), suggesting through environmental validations that yields were reduced due to sensitivity to heat during the floral transition. High nighttime temperatures during these study periods were also associated with a delay in pod formation and subsequent harvest. This fact highlights the need for multi-mechanistic measures to improve heat tolerance.

3.2 | Tolerance of ALB (*P. lunatus* L.) to Saline Soils

FAO (2023) estimates that salt-affected soils cover about 11% of the Earth's surface and about 10% of irrigated and rainfed cropland. Salt stress is a major constraint on crop productivity, with negative effects on germination, plant vigor, and yield (Tessema et al. 2023). Many irrigated areas are vulnerable to salinization from brackish water use due to limited freshwater resources and increased demand for food (Munns and Tester 2008). In this regard, research on salinity tolerance mechanisms highlights the particular sensitivity of the legume family to this stress (Maas and Hoffman 1977). According to the classification proposed by Maas and Hoffman in 1977 (Table 2), most legumes are considered sensitive or moderately sensitive to salinity. It is important to note that legumes, like other plants, experience salt stress directly, but their symbiotic associations also show increased sensitivity to salinity compared to their individual components. This effect is reflected at various stages, from the initial establishment of the symbiosis to nodule formation and functionality (Bruning and Rozema 2013; Khan and Basha 2015).

Most plants in the legume family can adapt to different types of soil if the soil is well drained. In their natural environment, some of these plants grow on eroded soils and soils with a pH between 4.5 and 6.2, but they can also grow on sandy soils, heavy clay soils, and slightly alkaline soils with high calcium content. It is important to note that the tolerance and adaptation of legumes to soil type can vary considerably from one crop to another. For example, *Altramuz angustifolius* does best in acidic

TABLE 1 | Important botanical and adaptive characteristics of tropical and subtropical grain legumes.

Region and name (presumed origin)	Scientific name	Chromosomes (2n)	Perenniality	Duration days	Plant type/size	Soil and climate tolerance/preference	Pests/diseases susceptibility	Purpose and use	Reference
I. Semi-arid regions (less than 500–600 mm annual rainfall)									
Bambara groundnut (Africa)	*Voandzeia subterranea*	22	A	90–150	Small, bunchy herb, prostrate, rooting branches, underground fruiting	Dry and poor soils; high temperatures	VL	The unripe seeds are eaten fresh, and the ripe ones are used as legumes	Duke (1981)
Kersting's groundnut (Africa)	*Macrotyloma geocarpum*	22	A	90–120	Prostrate annual herbaceous plant, main stem up to 10 cm long, creeping, with roots at the nodes; trifoliolate leaves	Dry, poor, sandy soil, high temperatures and sunshine	VL	Unripe and mature seeds used as a pulse	Duke (1981)
Moth bean(India/Burma)	*Vigna aconitifolia*	22	A	65–90	Slender, trailing hairy herb 10–30 cm tall	Dry, light sandy soils	M	Green pods as vegetable, ripe seeds whole or split as pulse. Forage, hay and green manure.	Duke (1981)
Cluster bean (India)	*Cyamopsis tetragonoloba* (L.)	14	A	90–120	Annual bushy branching up to 3 m high	Alluvial/sandy soils, high temperatures	VL	Green beans as vegetable leaves and stems for forage, dry seeds for mucilage	Duke (1981)
II. Semiarid to subhumid regions (600–900 mm annual rainfall)									
Peanut (Brazil)	*Arachis hypogaea*	40	A	100–150	Low bunchy herb: underground fruiting	Friable sandy loams	MH	Industrial oil, seed cake dry seeds for cooking and condiments	Duke (1981)

(Continues)

TABLE 1 | (Continued)

Region and name (presumed origin)	Scientific name	Chromosomes (2n)	Perenniality	Duration days	Plant type/size	Soil and climate tolerance/ preference	Pests/diseases susceptibility	Purpose and use	Reference
Pigeon peas (Asia, India, and South America)	*Cajanus cajan*	22 (44)	P	100–300	Height. Semi-woody shrub 1.5 to 5 m tall	Well-drained sandy/clayey silts	L	Dried seeds for legumes, immature seeds as vegetables Fodder and cover crop	Duke (1981)
Cowpeas (Nigeria)	*Vigna unguiculata*	22 44	A or SP	65–200	Twining, climbing, or procumbent herb or erect shrub from 20 to 120 cm tall	Well-drained sandy loam high temperatures	H	Dried seeds as legumes seedlings leaves pods and green seeds as vegetables cultivation of fodder and green manures	Duke (1981)
Mung bean/ black gram (India, Burma)	*Vigna radiata* and var. *mungo*	22 (24)	A	80–120	Erect–suberect, hairy herb: 50 to 130 cm tall	Well-tilled clay loams black cotton soils	M	Dried seeds split or sprouted green pods as table vegetable fodder	Duke (1981)
Horsegram (South Asia)	*Dolichos uniflorus*	24	A	120–180	Low, slender, semierect herb	Tolerates very poor soils	M	Dried seeds such as legumes and animal feed dry fodder and green manure	Duke (1981)
Hyacinth bean (South Asia)	*Lablab niger* (*Dolichos bean* or *Indian bean*)	22 (24)	SP	75–300	Intertwined herbaceous and shrubby forms	Well drained Tolerates poor and low fertility soils	M	Young pods and green beans as vegetables sexual seeds for legumes and feed for livestock forage	Duke (1981)
African locust (Africa)	*Parkia biglandulosa*	26	P	—	Tree 15–40 m or more in height	Wide range of alluvial soils	VL	Dried fermented seeds as flavorings, also cooked fruit pulp	Sampath and Ramanathan (1949)

(Continues)

TABLE 1 | (Continued)

Region and name (presumed origin)	Scientific name	Chromosomes (2n)	Perenniality	Duration days	Plant type/size	Soil and climate tolerance/preference	Pests/diseases susceptibility	Purpose and use	Reference
III. Subhumid regions (900–1200 mm annual rainfall)									
Phaseolus beans (Central America)	*Phaseolus vulgaris*	22	A	60–100	Dwarf bush for twining/climbing	Light sands to clay soils	VII	Dried seeds in the form of legumes, green pods, and beans as a vegetable, also for fodder	Duke (1981)
Tepary bean (Mexico)	*Phaseolus acutifolius*	22	A	60–90	Suberect herb bush y or recumbent 25 cm high	Dry soils do not tolerate waterlogging	M	Dry seeds for pulse, forage 5–10 toes of dry hay	Duke (1981)
Andean Pallar (South America)	*Phaseolus lunatus*	22	A	120–240	Annual erect shrubs and voluble or climbing shrubs	Sandy, clayey, deep loam Tolerates low fertility. Temperate, hot, arid climate Susceptible to extreme temperatures	Moderate tolerance to salinity, viruses, nematodes	Consumption of dry seeds and as a legume in the immature state of the grain. As fodder	Duke (1981)
Soybeans (Southeast Asia/China)	*Glycine max*	40	A	80–200	Erect bush to twist 20–180 cm	Tolerates some waterlogging	M	Industrial protein and oil green seeds as vegetables dry seeds as legumes leaf fodder stems	Duke (1981)
Rice beans (Southeast Asia)	*Vigna umbellata* (Thunb.)	22	SP	60–90	Erect–suberect/to twist 150 × 300 cm	Light to heavy soils	L	Dried seeds as legumes, green seeds, and pods as vegetables. Fodder	Duke (1981)

(Continues)

TABLE 1 | (Continued)

Region and name (presumed origin)	Scientific name	Chromosomes (2n)	Perenniality	Duration days	Plant type/size	Soil and climate tolerance/preference	Pests/diseases susceptibility	Purpose and use	Reference
Sword bean (Central America and Africa)	*Canavalia* spp. *Canavalia ensiformis* *Canavalia gladiata*	22 (44)	P	180–300	Bushy, straight 1–2 m large climber	Tolerates some waterlogging	VL	Green pods, vegetables, mature seeds, legumes, medicinal urease and lectin, vegetation for forage and cover	Duke (1981)

Source: Wall (1973).
Abbreviations: A = annual, L = low, M = medium, MH = medium high, P = perennial, SP = short-term perennial, VH = very high, VL = very low.

TABLE 2 | Salt sensitivity of the plant family Leguminosae.

Salinity level	Classification	Biomass production (%)
~3 dS/m (~30 mM NaCl)	Salt sensitive	80%
~6 dS/m (~60 mM NaCl)	Moderately sensitive	80%
~11 dS/m (~110 mM NaCl)	Moderately tolerant	80%
~16 dS/m (~160 mM NaCl)	Tolerant	80%

Source: Maas and Hoffman (1977).

soils, while chickpeas and lentils prefer alkaline soils (Kumar et al. 2022). As salinity is one of the most detrimental environmental factors limiting crop productivity, research to understand the mechanisms of salt tolerance in plants has developed (Munns and Tester 2008). Salt resistance involves adaptations to maintain physiological and biochemical homeostasis, including structural and molecular adaptations (Parida and Das 2005). For example, Andean crops such as Quinoa, Kiwicha, and Cañihua can increase the speed and percentage of germination under moderate conditions (100–150 mM NaCl, equivalent to 10–15 dS m^{-1}) up to high salinity conditions (Delatorre-Herrera and Pinto 2009; Paredes-López, Reguera, and Octavio 2023; Razzaghi et al. 2011). In addition, studies by Arteaga et al. (2018) reported the effects and salt stress response in four local Spanish fava bean (*P. lunatus*) cultivars that could tolerate three weeks of exposure to salinity up to 150 mM NaCl, proving that *P. lunatus* is moderately tolerant to salt and that the main mechanisms of adaptation to salt stress are the maintenance of high K^+ concentrations and the accumulation of proline in leaves.

The wild forms of "Pallar" prefer soils rich in organic matter and tolerate moist, deep, light to medium textured, well-drained, aerated, slightly acidic to moderately alkaline tropical soils with pH 6–7.2, although there are varieties that tolerate soil acidity down to pH 4.4. In general, it does not tolerate high salt concentrations, but some varieties, especially Andean varieties from Peru, do well in saline conditions (FAO 2018). For example, Machado et al. (2022) reported that as for soil pH, a range of 5.5 to 7.5 is recommended for cultivation and pH values of 4.3 to 8.3 have been reported in different studies.

3.3 | Biological Nitrogen Fixation and Legumes in Sustainable Agriculture

Biological nitrogen fixation plays a crucial role in sustainable agriculture, and ALB is emerging as a key player in this process. With its ability to form a symbiotic relationship with soil bacteria such as rhizobia, ALB provides a valuable contribution to soil enrichment with nitrogen, an essential nutrient for plant growth. Numerous studies have shown that lima bean is able to establish symbiosis with a variety of rhizobia, although it prefers *Bradyrhizobium* (Ormeño-Orrillo 2022), found in the Peruvian lima bean, mainly *Bradyrhizobium* strains distributed in four (geno) species, one of them, *Bradyrhizobium paxllaeri*, representing up to 80% of the *Bradyrhizobium* obtained in the central coast, where most of the lima bean is grown. It is interesting to note that all isolates of *B. paxllaeri* show very similar genomic profiles by PCR as well as identical or nearly identical housekeeping and symbiotic genes. On the other hand, Ormeño-Orrillo, Martínez-Romero, and Zúñiga-Dávila (2020) reported that *B. paxllaeri* is a common species in root nodules of lima bean (*P. lunatus*) in Peru. LMTR 21T is the type of strain of the species and was isolated from a root nodule collected from an agricultural field in the central Peruvian coast. Its 8.29 Mbp genome encodes 7635 CDS, 71 tRNAs, and 3 rRNA genes. All genes necessary to establish a nitrogen-fixing symbiosis with its host were present. The draft genome sequence and annotation have been deposited in the GenBank under accession number MAXB00000000 (Ormeño-Orrillo et al. 2017). In a context where water scarcity and climate change pose significant challenges to agriculture, understanding and optimizing biological nitrogen fixation in ALB is critical to promote sustainable agricultural practices and ensure long-term food security (Espinoza et al. 2022).

TABLE 3 | Proximal composition and mineral of raw dry beans of lima bean (*Phaseolus lunatus* L.) according to different investigations.

	Proximal composition (g/100 g dry matter)						kcal	Mineral (mg/100 g)									
Country	Protein	Ash	Fat	Water	Fiber	Carb	Energy[a]	Ca	P	Fe	Mg	Na	K	Cu	Mn	Zn	Reference
Peru	23.08	6.11	1.36	12.12	21.49[b]	69.46	286.20	79.19	359.73	7.58	NR	62.22	651.58	NR	NR	3.20	Reyes García, Gómez-Sánchez Prieto, and Espinoza Barrientos (2017)
Mexico	21.77	3.85	1.77	10.64	5.76	72.60	493.45	NR	NR	NR	NR	NR	NR	NR	NR	NR	Alcázar-Valle et al. (2021)
Indonesia	15.93	3.67	1.15	11.78	27.87[b]	68.89	NR	11.04	74.95	10.19	183.93	NR	38.21	NR	NR	NR	Palupi et al. (2022)
Nigeria	23.81	2.86	0.22	2.77	18.91[b]	73.11	NR	97.94	NR	3.29	114.59	187.46	840.08	1.06	3.35	3.38	Ezeagu and Ibegbu (2010)
Egypt	26.02	3.05	3.03	NR	25.84[b]	67.9	374.47	360.73	355.63	18.54	268.04	53.87	1373.29	1.74	1.07	4.17	El-Gohery (2021)

Abbreviation: NR = not reported.
[a]Kcal/100 g dry matter.
[b]Total dietary fiber.

4 | Hydric Stress: The Case of the ALB (Peruvian Pallar)

Water scarcity is emerging as one of the biggest current global challenges. In this context, the management of legume crops and drought research become even more critical, especially considering the anticipated increase of 2 to 4 °C in global temperatures during the next century (Lambers and Oliveira 2019). This is particularly true in semiarid tropical regions where a high temperature may further complicate the relationship between plants and water (Cerqueira et al. 2019; Lambers and Oliveira 2019; Martínez-Nieto et al. 2020). Low-altitude temperate and warm humid and semi-humid climates have been suitable for the adaptation of *Phaseolus*.

In addition, the ecological descriptors of this species indicate an altitudinal range of 0 to 2.386 m.a.s.l., an annual temperature range of 13.2 to 29.9 °C, and an annual rainfall range of 400 to 4.250 mm, which shows its ability to adapt to different climatic conditions (Barrera-Sánchez et al. 2020). Another study conducted by Machado et al. (2022) report that *P. lunatus* shows good growth performance under high-temperature conditions in terms of the number of flowers and pods produced, as well as lower values for the number of aborted pods, demonstrating its ability to adapt to different climatic conditions.

An interesting fact is that Martínez-Nieto et al. (2020) compared the Peruvian Pallar with Valencian varieties from Spain, such as "Pintat," "Ull de Perdiu," and "Cella Negra," in Europe. The evaluation of germination responses at temperatures of 15 °C, 20 °C, and 30 °C, observing high germination percentages for "Pallar" and "Pintat" at 15 °C and 30 °C. In addition, the response of germination to drought stress was presented by "Pintat," obtaining values higher than 50% for germination. In a recent study by Martínez-Nieto et al. (2022), it was found that *P. lunatus* L. demonstrates drought tolerance. This was deduced by evaluating and comparing the growth and biochemical responses of several genotypes, including those found in Valencian cultivars in Spain. When comparing Pintat and UII de Perdiu with the Peruvian Pallar, it was found that the latter exhibited similar levels of tolerance as the other varieties and even greater tolerance than the local cultivar Pintat during the growth phase under mild to moderate drought conditions with soil moisture levels of 40% to 60% and 20% to 40%. Both studies demonstrate that *P. lunatus* L. was minimally affected by water scarcity. However, genotype tolerance to water stress shows significant variance. This highlights the importance of precise genotype evaluation and selection for legume production. The "Pallar de Ica" is cultivated and developed in the Ica region, situated along the Pacific Ocean, approximately 300 km south of Lima, the capital of Peru. This region is considered a hyperbaric zone, with an average yearly precipitation of 100 mm (Correa-Cano et al. 2022).

There has been limited research on the cultivation of "Pallar" in the local territory, particularly in relation to abiotic factors. In addition, rising temperatures and other factors are expected to lead to changes in regional pest, disease, and weed distribution, posing new challenges for crop improvement and management programs. The Ica region is experiencing heat waves more frequently, as noted by Cuny, Shlichta, and Benrey (2017) and Valdez-Nuñez, Ríos-Ruiz, and Bedmar (2022). Preserving the diversity of Ica dry beans is crucial for Peru as a cultural heritage and as a source of local adaptations. According to Martínez-Nieto et al. (2022), the adoption of old and local varieties can enhance the valuation of marginal areas and enable entrepreneurs to earn higher incomes than with conventional ones. This is because consumers are increasingly willing to pay a premium for local products.

5 | Food Security

In recent decades, efforts have been focused on addressing hunger, malnutrition, and limited intake of essential nutrients, particularly in developing nations (Milião et al. 2022). Eliminating all forms of hunger and malnutrition by 2030 is a key objective of the United Nations Sustainable Development Goals (ODS), as hunger and malnutrition present a global challenge. The ODS 2 specifically addresses these issues (Sgarbieri, Antunes, and Almeida 1979; Vadez et al. 2012; von Braun et al. 2021). Currently, plants are being researched as a viable nutritional source for the population. *P. lunatus* L. stands out as an alternative due to its potential for promoting health and providing sustenance (Cuny et al. 2019; Didinger and Thompson 2022; Farinde, Olanipekun, and Olasupo 2018). On the other hand, legumes are regarded as one of the food products that have the least environmental impact concerning greenhouse gas emissions, land use, energy efficiency, eutrophication, and acidification per serving (Willett et al. 2019). Furthermore, following their harvest, legume seeds have a prolonged storage life and can be consumed throughout the year.

Table 2 displays reported values of the proximate composition and mineral content across different varieties of *P. lunatus* L. from diverse origins. The dried grains of the "Pallar" variety were analyzed using the Peruvian food composition table by Reyes García, Gómez-Sánchez Prieto, and Espinoza Barrientos (2017), which shows that the main components of the sample analysed are carbohydrates (69.46 g/100 g), followed by protein (23.08 g/100 g), dietary fibre (21.49 g/100 g), fat (1.36 g/100 g) and energy source (286.20 kcal). In terms of minerals, 'Pallar' is rich in potassium (651.58 mg/100 g), phosphorus (359.73 mg/100 g) and calcium (79.19 mg/100 g), with lower levels of sodium (62.22 mg/100 g), zinc (3.20 mg/100 g) and iron (7.58 mg/100 g). The protein content of the legume species *P. lunatus* varies according to ecological factors in countries. For instance, Egypt has the highest level of protein content with 26.02%, whereas Indonesia has the lowest with 15.93%. However, compared to other countries, *P. lunatus* has relatively higher levels of nutritional compounds, primarily protein, as documented in the literature. Therefore, despite the variability in protein content depending on the type of legume species, *P. lunatus* remains a potential source for protein extraction in the plant-based category.

In general, ALB have a higher amount of carbohydrates. According to research (Alcázar-Valle et al. 2021; Ezeagu and Ibegbu 2010), carbohydrates are the main component of legumes, whereas fat is reported to be at a low level. For instance, *P. lunatus* L. studied in different countries have reported carbohydrate ranges from 67.9 to 73.11% (Table 3). The carbohydrates that stand out in legumes are primarily starch. In contrast to cereals, legumes contain a larger amount of slow-digesting starch, which is the most favorable form of starch in the diet as it reduces the glycemic response and moderates' insulin levels in the blood (Chung, Liu, and Hoover 2009). Due to its functional properties, starch from pulses is an ideal ingredient for the production of healthy foods. In addition, mineral composition ranges have been reported for calcium (11.04–360.73 mg/100 g), phosphorus (74.95–359.73 mg/100 g), iron (3.29–18.54 mg/100 g), sodium (53.87–187.46 mg/100 g), Zn (3.20–4.17 mg/100 g) and potassium (38.21–1373.29 mg/100 g), the latter being predominant in Lima bean cultivars (Table 3). These variations in nutritional and mineral composition may be attributed to climatic factors, growth stages, and agronomic conditions of the variety (Adebo 2023). On the other hand, according to studies reported by Ccala Sucasaca and Ramirez Carrasco (2021), the "Pallar de Ica" contains significant amounts of limiting amino acids (lysine and methionine) and essential amino acids (valine and phenylalanine). However, further studies are needed to confirm these findings in greater depth.

"Pallar" is an essential component of food security as it has the potential to reduce malnutrition and undernutrition rates in developing countries. Its dietary fiber content also aids in preventing degenerative and chronic diseases, such as diabetes, cancer, obesity, neoplasms, and cardiovascular diseases (Toklu et al. 2021). Furthermore, studies indicate that factors such as phytic acid, tannins, trypsin inhibitor, and hydrogen cyanide, which are present in *Phaseolus* but not in cereals, can be partially or fully eliminated through common household or industrial processing methods such as cooking, soaking, roasting, and husking (Adebo 2023; El-Gohery 2021). From salads to soups and stews, "Pallar" is widely used in Peru's varied culinary landscape and is a staple ingredient. MIDAGRI (2022), documented and published a recipe book of these dishes, highlighting the vital role of "Pallar" in promoting food security in Peru. Despite its popularity, the commercialization of "Pallar" is limited to fresh pods and dried beans. Therefore, it is crucial to examine novel presentations and innovative ways of using "Pallar" as a valuable ingredient in various formulations. This will not only improve the quality of food products, but also enable the creation of value-added foods, while expanding the range of "Pallar"-based offerings.

Various options for exploiting these legumes are currently being studied, given the importance attributed to the cultivation of *P. lunatus* L. on the Peruvian coast, a region generally considered dry and hot. This raises interesting questions about the adaptation of Andean beans to extreme environmental conditions. This aspect could be the subject of future research to better understand how these conditions affect their ecology and development (Milião et al. 2022; Sahasakul et al. 2022; Sgarbieri, Antunes, and Almeida 1979; Toklu et al. 2021). Additionally, there is a notable lack of research at the agronomic and compositional level on all varieties of "Pallar." For example, the "Pallar mochero" is a particular variety, different from those known, which has black and white seeds that show the presence of phenolic compounds such as anthocyanins and others with potential biological and antioxidant activity that could be beneficial to human health and which have not yet been investigated. It is currently a forgotten resource and efforts to rescue it are still insufficient. Therefore, it is suggested that more research efforts are needed in this area, especially to fill this knowledge gap and improve the understanding of the characteristics and potential uses of these legumes.

6 | Conclusion and Perspectives

Ancestral Peruvian civilizations cultivated and utilized ALB, which has disseminated globally, particularly in tropical and subtropical regions such as the Peruvian coast. The Ica region represents a significant center of cultivation and commercialization of Pallar. On the other hand, environmental stresses (decrease in precipitation, increase in temperature, etc.) are key factors in the production and quality of crops. Therefore, greater effort will be necessary in the development of varieties better adapted to adverse conditions to meet the growing demand for food. As a crop that can thrive in diverse soils, including those affected by global warming and limited water resources, it offers promising avenues for research in social and economic development, as well as food security, as many research results highlight its nutritional value, in terms of plant-based proteins, dietary fiber, and minerals. In addition, pigmented wild species may have an important contribution in phytochemicals and/or bioactives of mainly phenolic nature.

Author Contributions

Isabel Milagros Gavilan-Figari: Conceptualization; Formal analysis; Investigation; Supervision; Writing – original draft; Writing – review and editing. **Marianela Inga:** Conceptualization; Formal analysis; Investigation; Resources; Supervision; Writing – original draft; Writing – review and editing. **Indira Betalleluz-Pallardel:** Conceptualization; Formal analysis; Investigation; Methodology; Supervision; Writing – original draft; Writing – review and editing. **Luz Marina Espinoza de Arenas:** Conceptualization; Data curation; Formal analysis; Visualization; Writing – original draft. **Raúl Comettant-Rabanal:** Conceptualization; Formal analysis; Investigation; Supervision.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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