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Exploring Lupins in China: Insights into Cultivation and Challenges for Sustainable Agricultural Development: A Review

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ABSTRACT

Lupin beans, a nutritious legume, are gaining popularity as a sustainable alternative protein source for both humans and animals, offering potential benefits over traditional options like soybeans. This review paper aims to provide a comprehensive overview of the present status of lupin cultivation, production and research in China. Through a systematic examination of recent literature, we analyze the cultivation practices, production trends and advancements in lupin research within the Chinese context. Lupins, originating from the Mediterranean region, exhibit diverse species distributed across various continents. While historically cultivated primarily for forage lupins have gained traction globally due to their adaptability to different climates and soil types. China is a big importer of lupins, but they are also trying to grow them domestically. This has been challenging due to factors such as the suitability of the local climate and soil and the management of diseases. In China, research is being conducted to improve lupin cultivation by studying genetic traits, disease resistance and soil adaptation. As lupins are known for their nutritional and environmental benefits, China's agricultural sector is expected to increase production.

Key words: Crop breeding, Genetic diversity, Global food security, Lupin, Sustainable agriculture.

Lupini or lupin (Genus- *Lupinus,* Family-Fabaceae), a native European legume, is gaining popularity as a promising source of protein. It's an important component of the cropping system in many countries such as Australia, South America and Europe (Abraham *et al.,* 2019; Kalembasa *et al.,* 2020).

In recent times, Lupin have gained attention in modern crop breeding efforts (Wolko *et al.,* 2010). While wild lupins have bitter alkaloids, hard seed coats and pods that scatter seeds when they mature, selectively bred domesticated lupins, have softer seeds that germinate immediately, lower levels of alkaloids and pods that do not scatter seeds, making thier harvesting more efficient. Four species *L. albus*, *L. angustifolius, L. luteus* and *L. mutabilis* have been accepted for human consumption purposes due to their richness in protein (range from 28 to 48 g/100 g), presence of favourable lipid (range from 4.6 to 13.5 g/100 g) with high content of unsaturated triacylglycerols and plenty of antioxidants such as carotenoids, tocols and phenolics (Castro *et al.,* 2022; Estivi *et al.,* 2023). Additionally, lupins have a low glycemic index (GI) and are incorporated into various food items such as pasta and white bread, effectively reducing their GI (Ramon *et al.,* 2005; Ji *et al.,* 2020; Krawęcka *et al.,* 2022). Lupin-containing products have been shown to reduce the risk of weight gain, heart disease, type 2 diabetes and gastrointestinal issues. They are also a good source of iron and can be bred to enhance oil content for protein and oil production (Lucas *et al.,* 2015; Villarino *et al.,* 2016; Gulisano *et al.,* 2019) The recognition of the nutritional attributes of lupins has led to their expanded incorporation in many food products such as in bakery and beverage products or as a pickled snack (Abraham *et al.,* 2019; Plustea *et al.,* 2022; Ho, 2023). Also, they are emerging as a sustainable and viable source of protein for feeding both monogastric and ruminant animals. They are expected to replace soybeans without compromising the quality of livestock products. (Abraham *et al.,* 2019; Zamora-Natera *et al.,* 2020). Table 1 provides a short description of the contents and characteristics of one of the lupin species *L. albus.* Fig 1 shows a lupin plant and its seeds.

However, utilizing lupin as a nutritious protein source demands attention to key quality traits, such as minimizing alkaloid content and focusing on the conglutin-γ protein fraction for managing insulin resistance and diabetes (Boukid and Pasqualone, 2022). Efficient food processing techniques have been suggested to optimize the use of lupin as a protein source.

Lupins are known for their adaptability to different soil and climate conditions.This adaptability has led to their cultivation in diverse regions worldwide. Several research

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are focusing on developing new varieties that can thrive in different environments (Wolko *et al.,* 2010). They are considered soil-enhancer crops that show considerable tolerance to abiotic stresses, making them suitable for phytoremediation of degraded and polluted soils (Quiñones *et al.,* 2022). Lupins establish symbiotic relationships with soil bacteria of the genus *Bradyrhizobium*, forming a special class of nitrogen-fixing root nodules known as lupinoid nodules which enrich the soil with nitrogen (Fernández-Pascual *et al.,* 2007). Also, several lupin species can develop cluster roots, which are stimulated by a deficiency of phosphorus in soils and play a significant role in mobilizing phosphorus by secreting organic acids, protons, phosphatases and phenolic compounds (Weisskopf, 2005). This makes lupin cultivation suitable in acidic soils and extremely useful given the fact that most of the cultivated soil in the world is now becoming acidic due to various natural and anthropogenic activities (Caon and Vargas, 2017; Maltare *et al.,* 2023). Hence, the ability of lupins to access sparingly available phosphorus (P) alongside the capacity for symbiotic nitrogen fixation makes them ideally suited to function as ecosystem engineers (Lambers *et al.,* 2013). Also, Lupins can develop cluster roots, which mobilize phosphorus in acidic soils (Weisskopf, 2005). This makes lupin cultivation useful given the increasing acidity of cultivated soil worldwide (Caon and Vargas, 2017). Hence, they can be considered as ideal ecosystem engineers due to their ability to access sparingly available phosphorus alongside symbiotic nitrogen fixation (Lambers *et al.,* 2013).

However, it is crucial to assess the current status of lupin cultivation worldwide which is essential as lupin has the potential to offer significant benefits, including higher crop yields, reduced reliance on pesticides and lower production costs.

This paper serves to provide valuable insights into the current status of lupine beans, including their susceptibility to various diseases. Additionally, the paper highlights the studies that have been conducted in China, offering a comprehensive overview of the state of research on this important crop.

Origin of lupin, worldwide distribution and current status of production

Lupins are believed to have originated in the Mediterranean region and the area surrounding it is considered the primary center of diversity for lupins(Abraham *et al.,* 2019). In Southern Europe, lupins were introduced in the eighteenth century, primarily for forage or as a coffee substitute They have been categorised into two broad groups: the Old World species found in the Mediterranean/North and East African regions and the New World group primarily in North and South America (Fig 2). Also, lupins are distributed through indigenous domestication in the Mediterranean and Andes

Table 1: Overview of key elements in L:albus.

Nutritional compounds	Potential contaminants	Antinutritive factors	Nutraceutical potential
Protein and amino acid	Mycotoxins (namely phomopsins)	Phytates	Appetite suppressor
Carbohydrates, polysaccharides, and dietary fiber	Pesticide residues	Alkaloids	Reduces the risk of cardiovascular diseases
Fatty acids	Heavy metal	Protease inhibitors;	Hypolipidemic action;
Macroelements and microelements		Lectins	Reduces hypertension;
Phytochemicals		Raffinose family oligosaccharides	Antidiabetic effect
			Improves bowel function
			Anticonvulsionant action

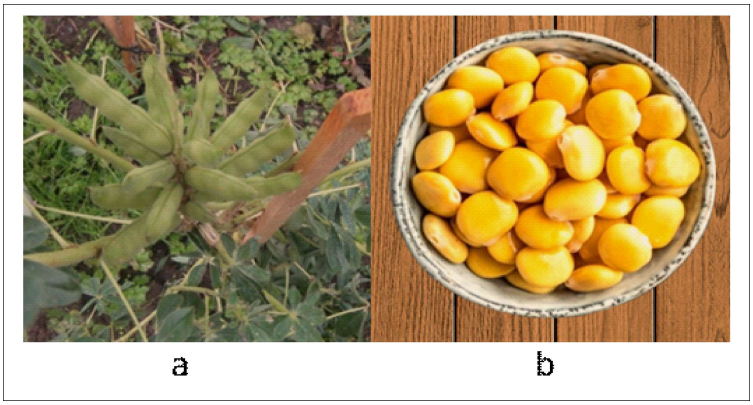


Fig 1: (a) Lupin plant; (b) Seeds of white lupins.

regions ranging across various climates and habitats. The cultivated species such as *L. albus, L. luteus, L. angustifolius* have long histories of domestication due to their tolerance for acidic, neutral and even slightly alkaline soils. However, they are less domesticated in North and East Africa. Lupins in these areas tend to be primarily wild species. The New World species from North and Central America show mountainous adaptation and are distributed along the western mountain ranges from Alaska to Central America having a mix of ornamental and forage species such as *L. polyphyllus and L. mexicanus*. *L. mutabilis* is the only domesticated lupin of the New World (Table 2), particularly from the Andean region. The region of the Atlantic coast boasts a rich variety of both simple and compound-leafed lupins which are centered around eastern Brazil, Uruguay, Paraguay and Argentina (Wolko *et al.,* 2010).

Production of lupins

Fig 3 shows the production of lupins worldwide in the year 2022 as per the Food and Agricultral Organisation. The global lupin cropped area reached nearly 1 million hectares in 2022, resulting in a total production of 1.645 million metric tons.

Fig 4 provides an overview of the global production of lupins. Despite lupins accounting for a relatively small proportion (0.3%) of all legumes produced worldwide between 2012 and 2022, their production quantities have shown a gradual upward trend in the past five years, with a 38% increase from 2018 to 2022. The observed surge in production implies a potential upswing in the demand for lupins. Globally, the primary producers of lupins are Australia, succeeded by Poland, Russia and Spain. Growing well in sandy, acidic soils, especially in Western Australia, lupins are used as green manure, fodder and organic material to improve soil health and stop erosion. Due to their nitrogen-fixing ability, lupins play a crucial role in crop rotation systems, supporting wheat and other cereals in Australia and Europe (Villarino *et al.,* 2016). Europe stands as a primary continent for the cultivation of white, blue and yellow lupin being used mainly as feedstock, though an increased demand for human consumption has been observed (Lucas *et al.,* 2015). In northern Europe, narrow-leafed lupin predominates. White lupin, with wider soil adaptability, thrives on loamy and light clay soils but is constrained by its long growing period, making it unsuitable for seed production beyond the Netherlands. (Gresta *et al.,* 2017). Lupins are cultivated in parts of Asia and their cultivation has gained attention in countries like China, where they have been recognized for their nutritional value.

Status of Lupin production in China

Lupin has recently been introduced in China, mainly for ornamental purposes and as a source of manure production (Zou *et al.,* 2019). Although lupins have long been included in the human diet their usage in the form of food for both humans and animals has not become popular in China yet.

However, China cultivates a variety of other legumes, with nine main species, such as Fava bean (*Vicia faba*), pea (*Pisum sativum*), common bean (*Phaseolus vulgaris),*

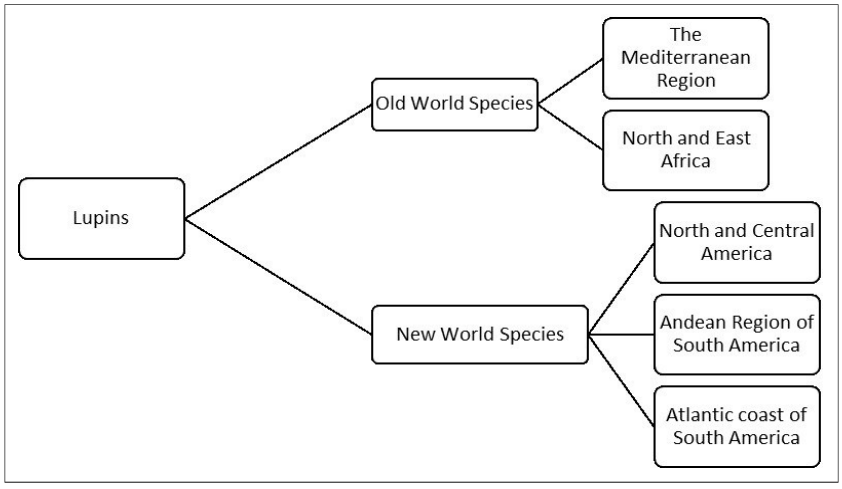


Fig 2 : Groupings of Lupins based on the origin and centre of diversity (Wolko *et al.,* 2010).

Table 2: Examples of species of lupins from old world and new world groups.

Origin	Lupin Species
Old world	*L. albus, L. angustifolius, L. luteus, L. hispanicus, L. micranthus, L. pilosus, L. palaestinus*
New world	*L. polyphyllus, L. arboreus, L. nootkatensis, L. mexicanus*

mung bean (*Vigna radiata),* adzuki bean (*Vigna angularis*), lentil (*Lens culinaris*), chickpea (*Cicer arietinum*), runner bean (*Phaseolus coccineus*) and cowpea (*Vigna unguiculata*) fava bean, pea, common bean, mung bean, adzuki bean, lentil, chickpea, runner bean and cowpea, being most commonly integrated into cropping systems. These legumes have historical roots in China, some dating back over 2000 years, contributing significantly to traditional and sustainable agriculture. However, there is an uneven distribution of major food legumes across different regions of China based on climatic conditions and geographical factors.

In comparison to other legume crops, the cultivation and production of lupin is less. Some varieties of lupins are sown in the fall in South China and early spring in North China (Zheng *et al.,* 1997). At present, *L. angustifolius* (also known as narrow-leafed lupin) is becoming more and more popular in China. Currently, there is no available

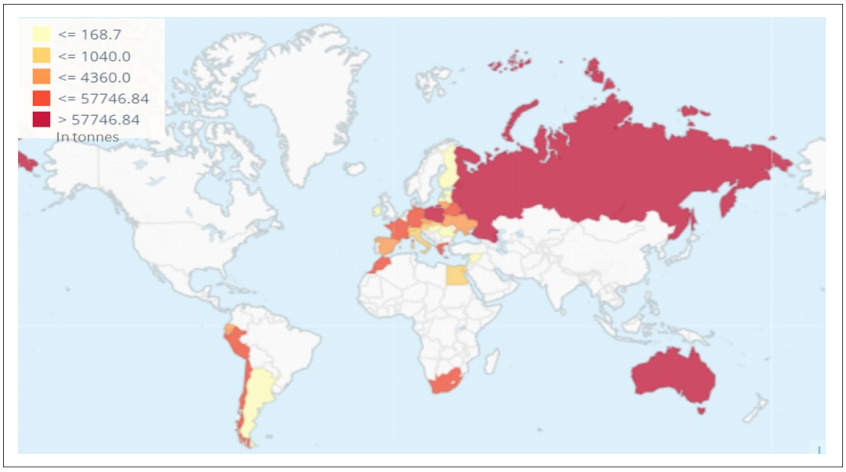


Fig 3: Production of Lupins by countries in 2022 (FAOSTAT, 2023).

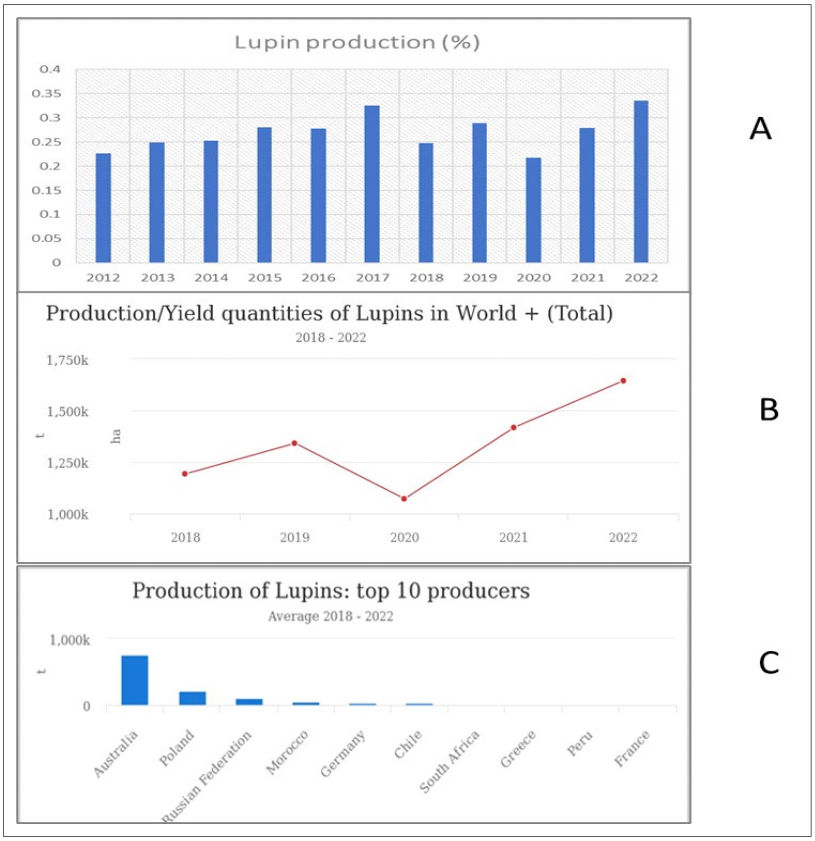


Fig 4: Proportion of Lupin production of all the legumes produced worldwide in the A-Last decade, B- Last 5 years e, C- Top 10 producers of lupins in last 5 years.

data on the production quantity of lupins in China. However, it should be noted that lupin products are being imported into China, where they account for roughly 33.98% of the total imports in 2022, making China the largest importer of lupin in the world. However, this trend is changing, as reflected in the fact that the volume of imports has decreased while exports of lupin have increased in 2022. Though, lupin exports by China accounted for only 0.04%, there was an impressive increase of 223.07% from the previous year.

Lupins can thrive in diverse soil and climate conditions, making them a highly valuable crop to cultivate (Hein, 2021; Notz and Reckling, 2022). However, in many Asian countries, such as China, lupins are not widely grown due to several constraints, such as unreliable yields, late maturity and poor tolerance of alkaline soils (Gresta *et al.,* 2017). In addition, the decline in soil quality and fertility, exacerbated by the long-term use of chemical fertilizers and pesticides, poses significant challenges to agricultural productivity and environmental sustainability. Acidic soils, resulting from chemical fertilizers, hinder the growth of many legumes, limiting their potential to improve soil health (Howey, 2020). However, incorporating lupins into agricultural practices could offer a solution. Lupins, known for their ability to fix nitrogen through biological nitrogen fixation, can contribute to intercropping and crop rotation systems that have been shown to effectively enhance biodiversity, improve pollination, more effective pest and disease control, better nutrient cycling, increased soil fertility and soil health and improved regulation of soil water (Chen *et al.,* 2023; Hai and Duong, 2024; Bagga *et al.,* 2024; Cho, 2024; Min *et al.,* 2024, Adewuyi *et al.,* 2023). In this way, China can reduce its overdependence on chemical fertilizers and cereal mono-cropping, promoting soil regeneration and sustainable agricultural practices for future food security and environmental well-being. The significance of this lies in the fact that China's capacity for crop and food production is not yet stable and lacks sufficient support from science, technology, innovation and informatics, while agricultural equipment requires improvement (Xu *et al.,* 2017).

Challenges in the cultivation of Lupins in China

Climatic suitability

Lupins need a specific climate for optimal growth, with temperatures ranging between 14°C to 25°C (Batzogianni and Tzikoulis, 2022). In addition, lack of rainfall and high temperatures can lead to flower and pod shedding, resulting in decreased seed yield (Lane *et al.,* 2019). Whether China's climate is suitable for lupin cultivation depends on factors such as temperature, rainfall and soil conditions. Lupins are more likely to be damaged during flowering and bud formation when the plant is growing rapidly due to frost damage caused by temperatures below -2°C as in the Northern China (Yu *et al.,* 2022). In southern regions with warmer temperatures, lupins may face heat stress during the summer months, severely affecting their production (Liu *et al.,* 2019).

Soil requirements

Lupins thrive in well-drained sandy loam, loam and clay loam soils with good structure and high organic matter content. They grow best in soils with a pH range of 4.5 to 7.5 and good fertility (Delane *et al.,* 1989; White and Robson, 1989). However, on fine-textured or alkaline soils, lupins produce lower grain yields. In China, legume-growing areas have a greater proportion of soil with alkaline pH, which can affect the growth of lupins (Howey, 2020).

Alkaloid content

Lupins are not a popular choice among farmers as compared to cultivation of peas and fava beans China due to the presence of alkaloids in their seeds. These substances are highly soluble and persistent, posing environmental risks. The residues of plants left in the field after harvesting contain about 30% of the alkaloid content, which can contaminate nearby environments during high-flow events. Alkaloids have a half-life of 36 to 60 days in water, allowing them to spread to new crops, soils and potentially affect animals (Rodés-Bachs and Van der Fels-Klerx, 2023).

Pest and disease management

Introducing a new crop can bring about new pest and disease challenges. Assessing potential pests and diseases that may affect lupins in China and developing management strategies is crucial to prevent crop losses. Lupin beans, like many crops, can be susceptible to various diseases that may affect their growth, yield and overall health. Table 3 provides the common diseases of lupins, its causal organism and common symptoms.

It is crucial to understand the diseases occurring in lupins to develop effective treatment and management plans. This ensures the success of the introduction and cultivation of lupins in new environments, promoting a healthy and robust agricultural system.

Early detection and timely intervention are crucial for minimizing the impact of diseases on lupin bean crops. Additionally, practising good agricultural hygiene and implementing integrated pest management strategies contribute to overall disease prevention and control. Conducting thorough research is crucial when dealing with plant-related diseases. This is especially true when a plant is introduced to a new environment, as it is important to understand how it will adapt to its new surroundings. China is currently introducing the Lupin plant and it is essential to gain insight into the research and development being done in the country to successfully integrate this new species.

Current research exploring the possibilities of lupin cultivation in China

The successful integration of lupin in China as a food source for cultivation requires a complete understanding

of its properties. Therefore, research on lupin has been increasing in various parts of the world, including China. In this context, understanding the status of lupin production and research in China is crucial to assessing the crop's potential in the country and beyond. Research on lupins in China has seen a progressive exploration across various facets of lupin cultivation, adaptation and genetic traits and has been discussed here. It commenced with Cheng *et al.* (2011) research on understanding white lupin root acclimation to phosphorus deficiency and root hair development. It provided insights into the adaptive mechanisms of white lupin in accessing unavailable phosphorus in the soil. Understanding the role of glycerophosphodiester phosphodiesterases (GPX-PDEs) in white lupin's response to phosphorus limitation can help in developing strategies to improve phosphorus uptake efficiency in lupin crops. By identifying the genes (GPX-PDE1 and GPX-PDE2) involved in root hair growth and development, this research can contribute to the breeding and genetic improvement of lupin varieties with

Table 3: Various diseases of lupins, their pathogen and symptoms.

Diseases	Pathogen	Symptoms
Anthracnose (Fig 5a)	*Colletotrichum lupini*	- Dark lesions on leaves, stems and pods - Premature leaf drop - Twisting of stems, petioles and pods - Necrosis with orange masses of conidia - Brown and wrinkled seeds
Phomopsis Stem Blight (Fig 5b)	*Phomopsis leptostromiformis*	- Lesions and discoloration on stems and leaves - Potential lodging - Diminished seed quality
Fusarium Wilt	*Fusarium spp.*	- Wilting, yellowing and stunting of plants - Plant death in severe cases
White Rot (Fig 6a).	*Sclerotinia sclerotiorum*	- White, fluffy growth on infected plant parts - Rotting of stems and root - Wide host range - Survival of sclerotia in soil
Rust (Fig 6b).	*Uromyces spp.*	- Orange-brown pustules on leaves - Reduction in photosynthetic ability
Root Rot (Fig 6c).	Various pathogens	- Wilting, yellowing and plant death - Favored by waterlogged soil conditions

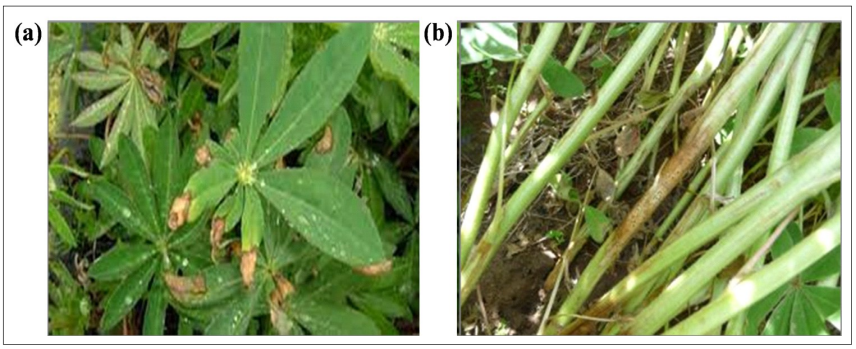


Fig 5: (a) Anthracnose, (b) Phomopsis stem blight.



Fig 6: (a) White rot of lupins, (b) Rust, (c) Root rot.

enhanced root architecture and phosphorus acquisition capabilities. The findings can also guide the development of targeted fertilization approaches and management practices to optimize phosphorus utilization in lupin cultivation, which can be particularly beneficial in phosphorus-deficient soils in China. Following this, Shi *et al.* (2017) presented a review on mycorrhizal relationships in lupines revealing the complex interplay between lupin species and soil conditions in mycorrhizal colonization. The research findings showed most of the lupin species are colonized by mycorrhizal fungi, although their root colonization rates were very low (<10%). Also, it was indicated that while some Lupinus species formed symbiotic relationships with arbuscular mycorrhizal (AM) fungi, others did not and colonization patterns varied based on host species and environmental factors. Additionally, the study examined the impact of AM fungi on lupine growth, nutrient uptake and metabolism, revealing significant variations in mycorrhizal dependency across different lupine species and AM fungal strains. These findings contribute to the understanding of mycorrhizal relationships in lupines, which can potentially inform the integration of lupin in China's agriculture by optimizing nutrient uptake and promoting plant growth through mycorrhizal symbiosis.

One of the important barriers to the cultivation of lupins is the risk of diseases, of which lupin anthracnose is the most devastating as it can affect any lupin crop in nearly every part of the world (Talhinhas *et al.,* 2016). In 2018, Zou *et al.* (2019). reported the first documented case of lupin anthracnose in China, highlighting the vulnerability of lupin crops to diseases and emphasizing the need for robust disease management strategies. One of the strategies involves the incorporation of desired genes of agronomic or end-use importance into breeding lines through plant breeding, to develop superior cultivars. To illustrate, in Australia, a specific dominant gene called "Lanr1" that provides resistance to anthracnose is widely utilized in the national lupin breeding program as a means to combat this disease (Yang *et al.,* 2012). Similarly, the ability of lupins to utilize phosphorus in deficient soil needs to be explored and integrated into plant breeding strategies as the global reserves of phosphorus deplete. Xu *et al.* (2020) provided genomic insights into white lupin's adaptation to low phosphorus conditions, unravelling prospects for breeding crops with heightened phosphorus use efficiency and aligning with global concerns for sustainable agriculture. Also, Ji *et al.* (2020) genetic diversity analysis in narrow-leafed lupin germplasm emphasized the significance of conserving and leveraging genetic variation, providing insights to steer genetic enhancement initiatives in lupin breeding programs. The study found a moderate level of genetic diversity and identified two subgroups within the narrow-leafed lupin accessions. It was found that the main source of genetic variation was within individuals rather than between different groups suggesting low variation among groups. The research emphasized the need to widen the genetic diversity of narrow-leafed lupin in China. Wang *et al.* (2022) added an evolutionary dimension to the discussion. By assembling the genome and identifying key genetic loci associated with domestication of lupins, the study not only contributed to the understanding of lupin's history but also opened avenues for knowledge-driven de novo domestication of wild plants. This novel approach aligns with broader global efforts to enhance crop plant diversity for sustainable food security.

The research studies conducted on lupin cultivation in China covered various aspects such as soil health, genomics, disease management and genetic diversity. These studies not only add to academic knowledge but also have practical implications for sustainable agriculture and global food security. Overall, the insights gained from these research endeavors are highly valuable for the agriculture sector and can help us in achieving our goal of sustainable and secure food production.

CONCLUSION

China's role in determining the future of lupin farming is crucial due to the various uses of lupins in agriculture, food and industry. Lupins are becoming increasingly popular worldwide and China has the potential to become a leading hub for lupin product innovation. The lupin seed market is expanding in China due to rising demand for nutritious and sustainable food, which could lead to a surge in lupin cultivation. Technological advancements such as precision farming, data-driven agriculture and biotechnological interventions can optimize lupin cultivation, improving yields and quality. Challenges such as climate variability, changing weather patterns and potential pests and diseases can pose threats to lupin crops, but climate-smart agricultural practices, resilient crop varieties and proactive pest management strategies can mitigate these challenges. Policy frameworks and government support can create an enabling environment for the lupin industry to thrive, through incentives for farmers, research funding and regulatory measures that encourage sustainable lupin cultivation practices.

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Authors' contribution

The author contributed toward data analysis, drafting and revising the paper and agreed to be responsible for all the aspects of this work.

Data availability statement

The database generated and /or analysed during the current study are not publicly available due to privacy, but are available from the corresponding author on reasonable request.

Declarations

Author declares that all works are original and this manuscript has not been published in any other journal.

Conflict of interest

The author declare that they have no conflicts of interest to report regarding the present study.

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