Journal of Food Legumes
38(3): 343-357, 2025
DOI: 10.53550/jfl.v38.i3.278

ISPRD 1987

Review Paper

Present scenario, challenges, future outlook and emerging market opportunities in lentil

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***Received:** July 11, 2025*
***Accepted:** August 14, 2025*

ABSTRACT

Lentil production in India is important to the country's agricultural environment and millions of people for their main source of protein. Its production demonstrates a blend of conventional farming methods and cutting-edge agricultural approaches, despite ongoing difficulties with disease and insect infestations, unstable weather patterns, and degraded soil. Lentil agriculture seems to have a bright potential in the future as a key crop in India's agricultural policy due to the growing demand for plant-based protein and enriching knowledge of the nutritional values of lentils. Crop management innovations can increase its yield and resilience to climate change. Examples of these innovations include better seed types and sustainable farming methods. Cultivation of lentils can also be facilitated by government programs that provide farmers with market access and subsidies. Collaboration between agricultural scientist's, policymaker's, and farmer's will be crucial to further explore these developments. Ultimately, the importance of lentil production to India's economy and food security may be ensured by concentrating on sustainable methods and improving value chains.

Key words: Breeding, Lentil, Nutritional, Production, Suitable cultivars

1. INTRODUCTION

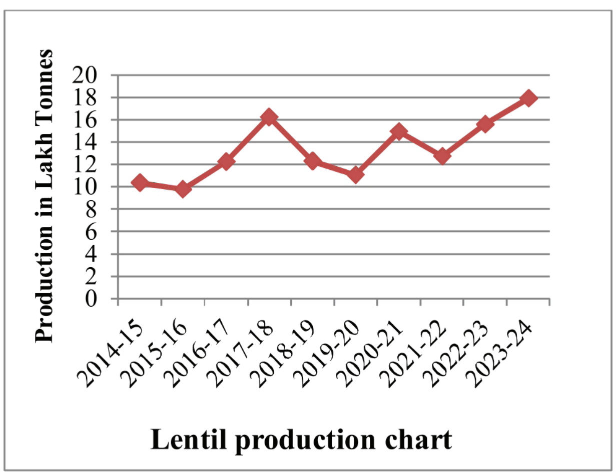
Lentil (*Lens culinaris* Medik) is a vital pulse crop in India, prized for its exceptional nutritional value and remarkable adaptability to diverse agro-climatic conditions. It is an indispensable component of the traditional Indian diet, playing a vital role in the country's culinary heritage. Lentils are a staple crop in the Indian diet, particularly for vegetarians, and are essential for food security. It is typically sown during the *Rabi* season. As a leading pulse crop, lentil production in India holds significant importance for both national food security and sustainable agriculture, playing a critical role in ensuring the country's nutritional well-being and environmental stewardship. The current state of lentil production in India, along with the challenges faced by growers, can be effectively addressed through cutting-edge agricultural research and technological advancements, ultimately unlocking the future potential for improved lentil cultivation. Despite its importance, the productivity of lentils (1023 kg ha^{-1}) (AICRP 2024) in India still lags behind the global average (1245.4 kg ha^{-1}) (FAOSTAT 2023). This disparity presents a significant opportunity for Indian farmers to enhance their agricultural and crop management practices, thereby boosting productivity and bridging the yield gap (Dutta *et al.* 2022). Lentil's are primarily cultivated as a rainfed crop, often succeeding in rice cultivation in the post-harvest period. This cropping system presents both opportunities and challenges. While integrating lentils into rice fallow systems can increase farmer's net returns, average yields remain limited by factors such as soil nutrient deficiencies and suboptimal agronomic practices (Saha *et al.* 2020, Kumar *et al.* 2020). Examining the future scenario, the prospects of lentils in India are buoyant with the advancement in agricultural technology and breeding programs aimed at developing high-yielding and disease-resistant varieties. Improved agronomic practices such as seed priming and nutrient management strategies for substantial yield gains in lentils were brought into focus by recent studies (Yadav *et al.* 2022). This places lentil in an indispensable position with in India's food security policy because they hold a significant value as an inexpensive source of protein in vegetarian diets (Singh *et al.* 2011). However, there are challenges mainly related to climate change, which might hurt agricultural productivity. Adaptive strategies are highly important in sustaining lentil production mitigating water stress and disease pressures as ascertained by Talukdar (2013), Tarannum *et al*. (2021). These are further compounded by increased trends in importation, which have been on an upward trend. Such increases in imports have underlined the need to enhance domestic production, which will cater to the increasing demand for domestic use with a subsequent reduction in dependency on imports. Hence, lentil production in India is both well established and in pressing need of critical research, policy-making, and farmer education concerning agricultural practices to realize its full potential as an important crop. With an improved productivity level in present trends, owing to support from technological enhancement, India has the opportunity for enhanced production of lentils and can further enhance food security and nutrition among its population.

2. PRESENT SCENARIO

The production of lentil in India has shown moreover an upward trend in the last 10 years. The lentil production status over 10 years is presented in Graph 1. Major producing states are Madhya Pradesh (48%), Uttar Pradesh (34%), West Bengal (8%), Bihar (7%), and Jharkhand (3%), and together this amounts to a large share of the total lentil sown area (https://upag.gov.in/) is presented in Figure 1. The productivity of lentil in India (1023 kg ha^{-1}) (AICRP 2024) is also lesser than the world average (1245.5 kg ha^{-1}) (FAOSTAT 2023) and the reasons for this can be improper agricultural practices with inappropriate crop management techniques. Lentils are typically raised as a rainfed crop and rice is mostly relayed after the crops. The timing of sowing also plays a crucial role in that it affects yield potential directly (Malik *et al*. 2015). Farmers confront issues like fertility deficiencies in soils, problems of pests and diseases, as well as climatic variability to a large extent which undermines production outcomes. For example, diseases like *Fusarium* wilt and Stemphylium blight may devastate lentil crops altogether, which inturn lowers their productivity and quality (Subedi *et al.* 2021, Arya *et al*. 2022).

3. NUTRITIONAL AND ECONOMIC IMPORTANCE

Lentils are among the richest sources of protein (21-25%) but also contain essential vitamins and minerals, and therefore it is affordable for low-income household consumers as a crucial part of an Indian diet (Singh *et al*. 2011, Salaria *et al*. 2022). Thus cultivation of lentils offers dual benefits including promoting human health and also safe guarding the environment. By enhancing soil fertility through atmospheric nitrogen fixation, it reduces our reliance on chemical fertilizers. Such a nature helps to make a parallel with sustainable agriculture and is part of an even broader vision that enhances food security in India. Economically, lentil production supports the livelihoods of millions of farmers across the country. The introduction



Graph 1. Year wise lentil production in India (In lakh tones), Source: https://upag.gov.in/

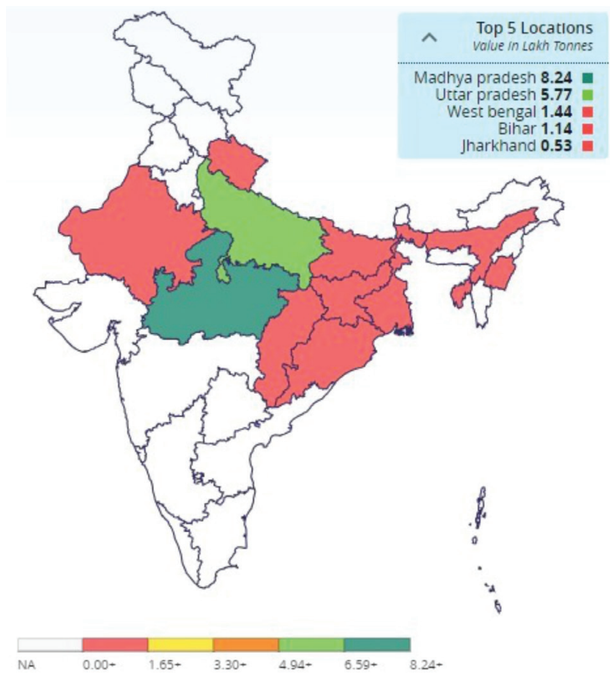


Fig. 1. Major lentil producing state in India, Source: https://upag.gov.in/

of lentils in cropping systems can increase farm income and enhance the shock resilience of farmers against market fluctuations. Studies reveal that the addition of lentils to crop rotation can increase the overall productivity and profitability of a farm (Reif *et al*. 2020, López-Ridaura *et al*. 2018). Despite their nutritional and economic significance, India's lentil production and productivity are failing to keep pace with the country's growing demand. As a result, lentil imports have risen sharply, from 63.97 thousand tonnes in 2003 to over 814 thousand tonnes in 2022, to meet the escalating domestic demand (Sah 2024).

4. CHALLENGES

Lentil production and productivity in India are hindered by numerous challenges, affecting their current performance and future potential. The challenges facing lentil production and productivity can be categorized broadly into four key areas including (i) environmental, (ii) biotic stresses and agronomics, (iii) breeding of suitable cultivars and (iv) socioeconomic.

4.1. *Environmental*

The major environmental challenges facing lentil production are drought and heat stress, especially in rain-fed farming systems where lentils are mainly grown. These stresses highly affect the reproductive stages consequently resulting in lower flower production and ultimately lowered yields (Baidya *et al*. 2020, Sellami *et al*. 2021, Mohammadi 2023). Climate change has escalated these problems leading to major causes of big losses in yields. For example, researchers have indicated that heat waves may reduce the yields of lentils by as much as 70% (Basu *et al*. 2022). In addition, lentils are also vulnerable to frost damage, particularly when grown in high-altitude plains during autumn, which significantly limits their growth potential (Baxevanos 2024). Climatic hazards, terminal heat, and drought stress the productive capacity of lentil to unprecedented levels with advancing climate change scenarios. Temperature changes are enhancing droughts significantly, there by triggering the study regarding the consequences it would under go on the entire process of lending. Reproductive-stage specific terminal heat damages lentils heavily, greatly causing a dent in the overall produce and quality. High temperatures may cause a decrease in flower production, pod number, and seed filling, leading to significant yield losses (Choukri *et al*. 2020, Choukri *et al*. 2022, Kumar *et al*. 2016). For example, heat stress during the reproductive stage has been reported to significantly limit growth and development, resulting in heavy losses in grain yield and nutritional quality (Choukri *et al*. 2022, Kumar *et al*. 2016). Plant reproductive stages are particularly responsive to heat stress because it threatens critical physiological mechanisms that must be in place for seeds to form. Drought stress often comes with heat stress and makes things worse for lentil crops. According to studies, the impact is more severe when both drought and heat stresses occur together rather than one after the other (Sehgal *et al*. 2017, Haddad *et al*. 2020). Drought conditions at critical growth stages result in flower and pod abortion, thus severely limiting economic yield (Nandi *et al*. 2022). In Mediterranean environments, lentils are confronted with terminal drought stress, which can influence yields with a reduction of 6% to 54% depending on water-limitation severity (Rahimi *et al*. 2016). It does not only result in a decline in yield but also in the well-being and sustainability of the plant, which could be manifested in reduced photosynthesis and water-use efficiency when stressed together (Sehgal *et al*. 2017). Several approaches have been identified to deal with these difficulties. One important breeding program for developing heat and drought-tolerant lentil varieties. Currently, tolerance to the stresses that caused such large area losses has grown in significance in lentil breeding where heat and drought are frequently critical factors affecting rainfed lentils, like during the years discussed above. Recently, adjusting planting dates (Ingle and Kavita 2022) as well as application of biostimulants at different phenologic stages have helped improve heat/drought stress susceptibility in lentils (Bhardwaj *et al*. 2021). For instance, foliar application of micronutrients has been shown to mitigate the damaging effects of heat and moisture stress, enhancing the performance of the plant under harsh conditions (Kumari *et al*. 2022). In addition, shifting lentil production to high-altitude areas where temperatures are relatively lower, and water might be available in greater quantities at critical growth stages, may serve as a possible adaptation option (Baxevanos 2024). This may help reduce the impacts of climate change on lentil production and ensure food security and sustainability as environmental stressors continue to rise. With the susceptibility of lentils to environmental stresses, adopting such climate-resilient agricultural practices would enhance resilience as well as sustainability (Hinz *et al*. 2020, George 2023).

4.2. *Biotic stress*

Agriculturally, several biotic stresses prevail in the cultivation of lentil, mainly consisting of the multitude of pathogens that cause the different diseases: such as *Fusarium* wilt, collar rot, root rot, *Stemphylium* and *Ascochyta* blights. Reports also indicate these as major productivity limiters for the crop with wide prevalence over the countries of interest (Kharte 2023). The loss of traditional landraces in regions such as Italy, where lentil cultivation has declined in favor of more profitable crops, further complicates the agronomic landscape (Reif *et al*. 2020). This loss not only reduces genetic diversity but also limits the options available for breeding programs aimed at improving disease resistance and yield stability. In addition,its production is increasingly threatened by a variety of emerging diseases, primarily caused by fungal pathogens. Among these, *Fusarium* wilt, caused by *Fusarium oxysporum* f.sp. *lentis*, is particularly devastating, leading to substantial yield losses and, in some cases, complete crop failure (Kharte 2023, Nisa *et al*. 2021, Tiwari *et al*. 2018). This disease has been reported across multiple regions, including South Asia and North America and its management remains a challenge due to its soil-borne nature and the pathogen's ability to thrive under favorable conditions (Tiwari *et al*. 2018, Yadav *et al*. 2017). Besides *Fusarium* wilt, Stemphylium blight caused by *Stemphyliumbotryosum* and *Ascochyta* blight caused by *Ascochytalentis* have become significant issues. Stemphylium blight has recently become a significant issue in countries such as Bangladesh and Nepal, where it impairs the productivity and milling quality of lentil crops (Adobor *et al*. 2022, Das *et al*. 2019). The disease often appears during warm and wet weather, especially after canopy closure during the growing season (Das *et al*. 2019, Subedi *et al*. 2021). Ascochyta blight is another serious threat; virulent isolates are increasing, which is breaking down resistance in previously resistant cultivars (Tullu *et al*. 2010a, Nawaz *et al*. 2022). Some recent studies indicate that climate change has altered the spectrum of the disease affecting lentils. The changing climate has triggered new disease complexes, such as the lentil blight complex, which is a mixed infection by Alternaria and Stemphylium species (Nazneen *et al*. 2024). This complexity complicates disease management strategies, as traditional methods may not adequately address the multifaceted nature of these emerging threats. Additionally, genetic variability among lentil cultivars is essential to generate resistant types; research, in this aspect, is focusing on the development of quantitative trait loci, QTL for resistance to those diseases (Ma *et al*. 2020, Roy *et al*. 2023, Gela *et al*. 2021). The biological controls and integrated pest management (IPM) practices are the potential methods which would reduce these disease impacts. For instance, the use of biocontrol agents and organic amendments has shown promise in managing *Fusarium* wilt (Kumari *et al*. 2020). Additionally, the identification of resistant germplasm from wild lentil species offers a potential avenue for breeding programs aimed at enhancing disease resistance (Podder *et al*. 2012). Modern breeding technologies, including genomic selection and gene editing, are also being promoted to speed up the development of resilient lentil cultivars (Roy *et al*. 2023). New diseases in lentil cultivation pose a significant threat to global food security. This would call for a holistic approach that incorporates traditional breeding, modern genomic techniques, and sustainable agricultural practices to improve the resistance of lentils to disease and make lentil production systems viable.

4.3. *Agronomic*

In addition to disease pressures, poor soil conditions are often a challenge to lentil cultivation, especially in rainfed systems where nutrient deficiencies can compromise seed quality and yield (Amir *et al*. 2024, Pragna 2023). The inconsistent rainfall patterns associated with climate variability also lead to reduced germination rates and poor seedling establishment, further impacting overall productivity (Amir *et al*. 2024).

4.4. *Breeding of suitable cultivars*

4.4.1. Lacking high input responsive cultivars

The development of responsive lentil varieties to high inputs is highly important to be able to raise lentil productivity, especially during the onset of new challenges posed by climate change, disease pressure, and the requirement for sustainability. The existing varieties of lentils are found less responsive to high inputs like fertilizer and water applications under different environmental situations. One of the most important difficulties lentil breeders face is that most varieties currently existing are not genetically diverse, which reduces the potential of developing medium to high-yielding, resilient varieties that will react productively to different agronomic inputs (Kumar *et al*. 2022, Tomar *et al*. 2023). A severe loss of genetic diversity has resulted from the process of domestication, a major limitation to lentil breeding programs aimed at the improvement of such traits as resistance to diseases and drought tolerance (Kumar *et al*. 2022, Tomar *et al*. 2023). For example, the introgression of genes from wild relatives, such as *Lens ervoides*, has been identified as a promising strategy to broaden the genetic base and improve disease resistance in cultivated lentils (Bhadauria *et al*. 2017, Adobor *et al*. 2022). In addition, the responsiveness of lentil cultivars to herbicides and their adaptability to diverse environments is critical for their successful integration into modern agricultural systems. Recent studies have strongly emphasized the imperative of developing machine-harvestable varieties of lentils that can ensure high yields through various weed management practices under differing environmental conditions. The stability under diverse conditions, therefore, provides a vital parameter for these cultivars, as varied environmental factors determine plant performance and yield (Kader *et al*. 2022, Balech *et al*. 2023). Drought stress is another key determinant of lentil productivity in arid and semi-arid areas. Some lentil varieties are more drought-tolerant than others and their selection and breeding can help develop resistance (Morgil *et al*. 2017, Idrissi *et al*. 2016, Ghanem *et al*. 2017). The development of cultivars that can effectively utilize available water resources and maintain productivity under drought conditions is essential for ensuring food security in regions prone to water scarcity (Ghanem *et al*. 2017). Moreover, the emergence of diseases such as Stemphylium blight and Ascochyta blight poses significant threats to lentil production. Resolving the cultivated and wild lentil germplasm for the identification of resistance genes to be incorporated into breeding programs is essential for developing resilient cultivars (Podder *et al*. 2012, Tullu *et al*. 2010a). Modern breeding techniques involving marker-assisted selection can speed up the development of cultivars responsive to high inputs that are resistant to prevalent diseases (Adobor *et al*. 2022). To address the low number of high input-responsive lentil cultivars, it would require a comprehensive approach, which involves widening the genetic base, developing drought and disease-resistant varieties, and adaptability to various agricultural practices.

4.4.2. Lack logging tolerance

Lentils are found to have a very poor tolerance for water logging, especially in situations of long-term water logging. It has been proven that water logging stress drastically affects the growth and biomass yield of lentil varieties. It was reported that the total biomass was reduced by 49.3% when water logging was applied for 14 days compared to a 31.5% reduction after 7 days of water logging stress (ELİŞ 2023). This highlights the detrimental effects of excessive soil moisture on lentil plants, which can lead to severe yield losses. The physiological responses of lentils to waterlogging stress are complex and involve various morphological and biochemical changes. Waterlogging can disrupt root respiration, leading to anaerobic conditions that hinder nutrient uptake and overall plant health (ELİŞ 2023). Additionally, lentils are responsive to other abiotic stresses like drought and heat, which might exacerbate the stress of waterlogging. For instance, the combination of drought and heat stress has been reported to harm growth and yield, meaning that lentils are highly susceptible to multiple stress factors (Sehgal *et al*. 2017, Choukri *et al*. 2020). Besides waterlogging, lentils are also sensitive to salinity and drought conditions. In plant life, during the seedling phase, salinity stress can further exacerbate issues that hamper growth and biochemical procedures and complicate further survival with adverse conditions, thereby affecting successful adaptation (Yasir *et al*. 2021). Drought is described by various authors worldwide as one of the most restrictive factors for growing lentils as the arable lands are facing this constraint (Giannakoula *et al*. 2012). The genetic diversity within wild lentil species can also provide potential pathways for breeding programs that would help improve drought tolerance to reduce some adverse effects of waterlogging and other stresses (Gorim and Vandenberg 2018, Gorim and Vandenberg 2017a). Physiological mechanisms of stress tolerance in lentils are yet to be unveiled. For example, osmopriming has been found to enhance lentil performance both under optimal and water-deficit conditions by modifying physiological processes (Farooq *et al*. 2019). This implies that although lentils are not naturally tolerant to waterlogging, there are methods that could improve their tolerance to these stressors. The interplay of waterlogging with other abiotic stresses such as drought and salinity further complicates the cultivation of lentils, which requires a multifaceted approach to improve their resilience through breeding and management practices.

4.4.3. Lacking early maturing and high biomass cultivars for rice fallow areas

The development of early maturing and high biomass lentil cultivars is important for optimizing agricultural productivity in rice fallow areas (19.6 MHA in India) (Kumar *et al*. 2020), especially in regions with climatic challenges such as terminal heat stress and erratic rainfall. Early maturing lentils can take advantage of residual soil moisture, which is essential in rainfed conditions, thereby increasing biomass production and overall yield. Such conditions could also be very effective in improving biomass and yields when lentil cultivars exhibit early phenology with rapid ground cover, to escape pre-monsoon showers occurring coincidentally around harvesting periods, for example, as demonstrated by Layek *et al*. (2021). The current developments in the techniques of plant breeding, with a special mention of InDel markers, help to identify early maturing genotypes of lentils. These markers are critical for breeding programs aimed at developing cultivars that can withstand terminal heat stress, which is becoming increasingly important in the context of climate change (Shivaprasad, 2024). The integration of these genetic tools into breeding programs can enhance the resilience of lentil crops, ensuring better yield stability in the face of environmental variability (Neilsen *et al*. 2022). However, the identification of high harvest Index(HI) and biomass lentil varieties is also crucial for germplasm. Research studies indicate that there exists a huge difference in HI and biomass between the lentil varieties, thus further breeding is necessary to develop varieties with better characteristics (Neilsen *et al*. 2022). The combination of high biomass with early maturity potentially enhances yield potential, especially where the rice crop needs to be planted and harvested on time for proper development of the rice plants (Iqbal *et al*. 2021). Some agronomic techniques like relay sowing have already been reported to increase lentil productivity under rice-fallow systems. Relay-sown lentils can mature in time to prepare the land for subsequent crops, thus intensifying cropping systems and improving land-use efficiency (Malik *et al*. 2015). The technology maximizes the utilization of the available moisture and contributes towards soil health through breakage of fallow. Additionally, the adoption of nitrogen management strategies has been correlated with improved early maturity in lentil varieties. Nitrogen fertilizer application should, therefore be balanced to optimize the production of biomass and yield and is likely a good management option for the intensification of lentil cultivation in rice fallow areas (Zakeri and Bueckert 2015). Genetic variation in lentil germplasm also plays an important role; an increase in genetic diversity has improved resistance to both biotic and abiotic stresses, ultimately developing high-yielding and early-maturing varieties (Naik 2024). The combination of genetic advancements and innovative agronomic practices with an effective nitrogen management system can ensure a significant jump in productivity potential for early maturing lentils in rice-fallow areas. This multi-progressive approach contributes to addressing challenges posed by climatic variability to the immediate advantages of sustainable agricultural systems in these areas.

4.5. *Socio-economic*

Socio-economic factors also influence the choices of farmers, financial literacy and resource utilization (Das and Maji 2023). The cultivation of lentils is often overshadowed by other cash crops, which may discourage the producers from offering into the production of lentils. This is because of economic pressure as evidenced by the replacement of traditional lentil farming with cash crops in several regions (Reif *et al*. 2020). The market for lentils is also constrained by a lack of varieties adapted to varied growing conditions, coupled with inadequate processing facilities for lentil products (Roos *et al*. 2018). The consumer's awareness of lentil nutritional values is still at a low level, which inhibits demand and further slows market growth (Roos *et al*. 2018). Never the less, there is some hope in the prospects for lentil production. The increasing global focus on sustainable diets and plant-based proteins presents an opportunity for lentils, given their high protein content and environmental benefits, such as nitrogen fixation (Gustafson 2017). Prospects for lentil production hinge on addressing these challenges through targeted research and development. Investments in breeding programs that improve genetic diversity and develop cultivars that can withstand abiotic stresses are crucial (Tullu *et al*. 2010b, Singh *et al*. 2018). Improving lentil breeding for resistance to biotic and abiotic stresses could enhance productivity and resilience in changing climates (Keneni and Ahmed 2016). Climate change will also impact lentil farming, as the changes in weather patterns may exacerbate the current challenges (Warne *et al*. 2019, Mamakhai and Zagoruiko 2022). There are significant opportunities for rejuvenation and growth. The challenges can be addressed through targeted research, improved farming practices and enhanced market strategies for the future of lentil cultivation.

5. FUTURE OUTLOOK

The lentil cultivation in India considering the research and technological developments indicatesa promising future of lentil production in Indian agriculture growth. High-yielding and disease-resistant lentil varieties can be developed through genomic-assisted breeding, which has the potential to enhance productivity (Kumar *et al.* 2021, Salaria *et al.* 2022). The use of integrated pest management (IPM) strategies may help to minimize the impact of diseases and peat on crops, thereby increasing crop health and crop production (Dhull *et al.* 2023, Arya *et al.* 2022). According to Rahaman *et al.* (2023) innovative agronomic practices, such as precision farming and the use of bio-fortification techniques, can make lentil nutritional quality more enhanced and contribute to higher values for lentils in the marketplace. Promoting sustainable agricultural practices, such as organic farming and conservation agriculture in furthering soil health and long-term productivity for increased yield further enhances the overall productivity of crops. Subsequently, other development areas in the lentil sector include support to lentil farmers by the government through subsidies, training programs, and credit. In India, researchers have focused on high-yielding, disease-resistant, early-maturing lentil varieties. Singh *et al.* (2022), showed that advanced interspecific derivatives could potentially lead to high-yielding varieties suitable for Indian agroecological conditions, consequently the importance of breeding programs that are based on transgressive segregation and heterosis in establishing desirable traits. The International Center for Agricultural Research in the Dry Areas (ICARDA) has also contributed a great deal to genetic diversity through a significant amount of germplasm as well as traits for better breeding. This adds genetic variation to develop lentil varieties that can perform satisfactorily in different environments and be more resistant to biotic stresses as stated by Vega *et al.* (2022). Participatory approaches in research in agriculture have also received much attention, especially in Ethiopia, as Mihiretu *et al.* (2019) found that farmers prefer local lentil varieties over improved ones because they see little difference in yield. This highlights the need for extension services to clearly explain the benefits of modern farming practices and improved varieties. Similar participatory assessments may also be used in India to enhance the acceptability of new farming practices by farmers, as it would address local needs and conditions. Furthermore, innovative agronomic practices such as intercropping and optimized row spacing have shown potential for enhancing lentil productivity and fighting effectively with weed infestations. It has been found that where other crops like naked oats are intercropped with lentils, there is minimum competition from weeds, thereby optimizing seed yield when farmed organically (Kraska *et al.* 2019). This would not only prove beneficial in enhancing yields but would also make farming sustainable by ensuring the use of minimum chemical herbicides. Integrated fertilizer strategies that overcome low soil organic matter have been developed to overcome the situation. For example, in Bangladesh and other similar regions, intensified fertilizer management practices are essential for enhancing lentil yields, report Kobir *et al.* (2020). Such integrated approaches can ensure long-term sustainability in lentil production and soil health. International concern for the lentil breeding program for nutritional quality improvement is evident. National programs in various countries, in collaboration, are working to develop lentil varieties rich in essential micronutrients like iron and zinc to combat global nutritional deficiencies (Gaikwad *et al.* 2020). Such efforts are most relevant to regions where they are staple foods providing large proportions of proteins along with significant minerals.

6. EMERGING MARKET OPPORTUNITIES

6.1. Rising domestic demand for lentils

An increase in demand for lentils within a country is a complex issue because of multiple socio-economic and health-related factors. Studies have been documenting an increased consumption of lentils over the past years because of changes in dietary preferences, higher health consciousness and population growth. For instance, in Nepal, the national demand for lentils increased to 359,000 tonnes in 2020, after it surged 37% higher compared to 2015. Projected demands for the year 2025 indicate this to increase up to 390,000 tonnes (Gautam *et al.* 2023). Lentil consumption is growing globally at a pace greater than population growth, mainly driven by nutritional and versatility in kitchen uses (Fratini *et al.* 2014, Gorim and Vandenberg 2017b). It is known that lentils are highly rich in nutrients with virtually very high protein, fiber, vitamins and minerals which describe their popularity in many cuisines as a staple in many forms of food (Montejano-Ramírez 2024, Reif *et al.* 2020). They are especially valued for their low glycemic index and the possibility of preventing chronic diseases such as diabetes and heart disease (Aguilera *et al*. 2010, Ganesan and Xu 2017, Rico *et al*. 2021). Subsequent epidemiologic studies document the frequent consumption of lentils with better glycemic control and lowering cholesterol levels, thus propelling their further demand as a health-promoting food (Bielefeld *et al*. 2020). The economic aspect of lentil production and consumption cannot be overlooked. For the most part, the domestic production of lentils in every country is unable to meet its domestic demand, hence promoting increased imports in countries such as India which imported approximately 0.65 million tonnes in 2022 to suffice its domestic needs (Sah 2024). Such an import dependency also opens avenues for increasing local production through the improvement of seed variety and farming practices (Yigezu *et al*. 2022). For example, the adoption of improved lentil varieties led to a drastic increase in yield in Bangladesh, thereby significantly reducing import dependency (Yigezu *et al*. 2022). Other reasons include cultural aspects beyond the health and economic factors that cause this recent demand increase for lentils. Traditionally, in South Asia, lentils have gradually become an integral part of staple diets as consumption of these food items has been strictly aligned with their associated culinary customs (Ariyawardana *et al*. 2015). Besides all these qualities, other factors that make lentils an attractive source of food are how easy it is to cook them-it is quicker and requires less energy than the majority of legumes-have gained importance as expressed by Fratini *et al*. (2014), Warne *et al*. (2019). As environmental issues attract more attention to consumers, their perception of lentils as a food nutrition source that can replace animal proteins is further developed. This aspect is harmonious with wider tendencies concerning the sustainable consumption of food (Warne *et al*. 2019). The rising domestic demand for lentils is supported by a convergence of health benefits, economic opportunities and cultural significance. As production systems adapt to meet this demand, there is a substantial opportunity for lentils to play a pivotal role in food security and nutrition, particularly in regions where they are traditionally consumed.

6.2. *Export markets and international trade prospects*

The prospects for international trade in lentils are shaped by various factors, including competitive advantages, trade policies, and global market dynamics. Nepal, for instance, has demonstrated strong competitiveness in lentil exports, with a revealed comparative advantage (RCA) greater than 1, indicating a potential for growth in international markets (Ghimire, 2024). However, the country faces challenges such as a fluctuating trade specialization index and a high concentration in its export market, which can pose economic risks (Ghimire 2024). The liberalization of global trade has generally led to increased economic activity, benefiting agricultural exports (Atagher 2022). Countries that embrace trade openness tend to experience faster economic growth, which can enhance their export capabilities (Mbogela 2019). The COVID-19 pandemic has had a complex impact on trade, with some sectors, including pulses, facing declines due to disruptions, while others, like Canadian agricultural exports, saw unexpected booms due to shifts in global demand (Barichello 2020, Barichello 2021). Future prospects for lentil trade will likely hinge on the ability of producing countries to adapt to changing market conditions and consumer preferences, particularly as demand for plant-based proteins continues to rise globally (Oduro-Yeboah *et al.* 2022). Additionally, the integration of innovative agricultural practices and improved varieties can enhance production efficiency, further supporting export growth (Reddy *et al*. 2022, Vega *et al.* 2022). Globally lentil exports were 4.312 mt in 2022 with a worth of $4.24 billion with South Asia and the Middle East as major markets. Canada (1.892 mt), Australia (1.045 mt) and Türkiye (0.499 mt) were major lentil-exporting countries. Canada dominated both production and exports, generating $1.634 billion in export revenue, while Australia exported more than it produced, likely due to re-exports. India, despite being a leading producer, plays a modest role in exports due to high domestic demand. The UAE, without local production, has become a top exporter through re-exporting lentils. Overall, Canada and Australia are the foremost players in lentil production and export (Shaikh *et al*. 2024). India, Bangladesh, Türkiye, UAE and Iraq, were major importing countries in the world which shared 55% of total global imports. Despite being a leading lentil producer, India imported 0.656 million tonnes (mt) of lentils, valued at $0.54 billion, to meet domestic demand. Interestingly, the UAE emerged as a significant importer and re-export hub, despite having minimal local consumption and production (Shaikh *et al*. 2024).

6.3. *Emerging role of plant protein-based ready-to-eat food industry*

The role of emerging plant protein, especially from lentils, is becoming more attention-worthy in the ready-to-eat food industry because of the nutritional value it provides, coupled with its eco-friendliness and versatility in food formulations. Lentil protein is becoming one of the major alternatives to conventional animal and soy proteins because consumers are now embracing plant-based diets and the demand for healthier foods (Khazaei *et al*. 2019). Key products from lentils include protein isolates, protein concentrates and flour; the protein isolates segment is the largest of these, which accounted for approximately 46.7% of the market value in 2020 (Transparency Market Research 2025). The market for end-use lentil protein is also segmented into different categories including baby food [Rice-o-Lentils manufactured by Rorosaur Baby Food; Only Organic baby food manufactured by Organics, Organix baby meal manufactured by My Baba; Organic Lentils manufactured by Gefen), sports nutrients [Whey Protein Manufactured by Trunativ, Lentil protein powder Manufactured by Urban platter and whole masur brown lentils Manufactured by Pride India; Sweet and Sour Lentils manufactured by Gym Kitchen], animal feed [Bindox plus Manufactured by Rannim Pharma Ceuticals Private Limited and Bio Blooms Manufactured by Bioblooms Agro India Private limited], food processing [Green Lentils Manufactured by Birch & Meadow and New Puy Lentils Cooked Manufactured by Merchant Gourment] and nutraceuticals (Pasta Natura's tricolor organic Fusilli). Lentil food processing is a major market segment, which shared 70.5% of the total market value in 2020. The global lentil protein market was valued at US$112 million in 2020 and is projected to reach US$181 million by 2030, growing at a compound annual growth rate (CAGR) of 4.8%. (Transparency Market Research 2025). The rising adoption of plant-based proteins is fueling demand for lentils in both developed and developing countries (Kumar *et al*. 2021). The global lentil protein market is dominated by Europe, which accounts for over 40% of the market share, followed closely by North America with a 33.3% share (Transparency Market Research 2025). Besides lentils being high in protein, they also have an advantageous amino acid profile, thus applicable to food production (Sá *et al*. 2023, Song *et al*. 2022). Lentil protein is attractive in nutritional profiles because of the presence of crucial amino acids like lysine and leucine, essential for human health (Subedi *et al*. 2020, Sá *et al*. 2023). This high protein content, which coupled with high digestibility puts it in excellent favor for use as an ingredient for ready-to-eat foods and snacks along with other foods, can result in the food being formulated containing higher nutritional benefits when lentil proteins are introduced (Dhull *et al*. 2023). Also, the versatility of lentil protein gives it the capability to be incorporated into several methods of food processing, including extrusion, which is the preferred method for preparing ready-to-eat snacks and cereals (Cotacallapa-Sucapuca *et al*. 2021, Pasqualone *et al*. 2020). Extruded lentil flours can also be effectively processed to obtain a product with an acceptable texture and flavor, further expanding its applicability in food processing (Ek *et al*. 2021). The extrusion process not only improves the digestibility of lentil proteins but also enhances their functional properties, making them suitable for incorporation into a wide range of food products (Cotacallapa-Sucapuca *et al*. 2021). With their nutritional benefits, lentils are also associated with lower environmental impacts compared to animal protein sources. Lentil cultivation contributes to sustainable agriculture, like nitrogen fixation, which can enhance soil health and reduce the usage of synthetic fertilizers (Warne *et al*. 2019). This sustainability aspect also aligns with the growing awareness of consumers regarding the environmental footprint of their food choices, thereby further driving demand for plant-based proteins in the ready-to-eat food sector (Meinilä *et al*. 2022). In addition, there is significant research and development in the food industry regarding combining lentil proteins with other types of plant proteins, such as whey. This may improve their functional properties and overall quality (Alrosan *et al*. 2023). This innovative approach would overcome some of the limitations related to lentil proteins, such as solubility and emulsifying properties, providing broader applications in food products (Alrosan *et al*. 2023). Introducing lentil protein into the ready-to-eat food industry has a good future in filling consumers' demand for nutritious, sustainable, and convenient food options. As plant-based foods grow more in popularity, lentils have a vital role to play in shaping the future of food formulations for healthier diets and sustainable food systems.

6.4. *Exploring Regional Lentil Consumption Patterns*

The diverse lentil-based cuisines of various countries offer a unique opportunity to explore and understand regional lentil consumption patterns.

Lentil-based cuisines vary greatly across the globe, reflecting local flavors and traditions. In South Asia, popular dishes include Masoor Dhal Pulav, Masoor dal, Dal Tadka, Sambar, Khichdi, and Papad. Persian cuisine features Adasi (lentil stew) and Adas Polo (lentil and rice dish). Africa boasts a diverse array of traditional lentil dishes, such as Misir Wat (Ethiopia), TsebhiBirsen (Eritrea), Adess (Algeria), Bsissa (Tunisia and Libya), Koshari (Egypt), Hlalem (Tunisian pasta) and Lentil Soup (Morocco). The Arab and Mediterranean regions are home to popular lentil-based dishes like Mujaddara, Shorbeh (Iraqi lentil soup), ShaurabatAdas (lentil soup from Kuwait, Lebanon and Syria), Matany, and Maloonga (Yemen). In Europe and North America, notable lentil dishes include Le Puy green lentils (used in French ragout), Fakes (Greek lentil soup), Fakorizo (Greek lentil and rice dish), MercimekKöftesi (Turkish lentil meatballs), Greek lentil salad, Sopa de lentejas (Spanish lentil soup), Bulgarian lentil soup, Pilaf (U.S.), Mujaddara and Cajun lentil stew (Louisiana). These dishes are flavorful, versatile, and nutritious, reflecting diverse regional cuisines (Shaikh *et al*. 2024). The diverse use of lentils in various traditional dishes presents an opportunity to capitalize on regional consumption patterns by exporting lentils to non-producing countries.

7. CONCLUSION

In conclusion, lentil production is indispensable for food security and nutrition and indeed millions of farmers livelihoods in India. Though the status today reflects a considerable contribution to global lentil production, challenges of productivity, climate change and socio-economic issues should be overcome in order to take full advantage of the crop. By means of newer agricultural research, sustainable agriculture practices, and supportive policy will improve lentil production in India, thus ensuring the stable supply of this important pulse crop for generations to come. Last but not the least, enhancing the genetic potential of lentil is essential for lentil to become a mainstream crop. Innovative breeding programs might play a crucial role in the development and improvement of lentil cultivars, addressing various challenges such as disease resistance, nutritional enhancement and adaptation to changing environmental conditions. The integration of molecular breeding techniques, such as quantitative trait locus (QTLs) mapping, has enabled the identification of genetic markers associated with disease resistance, facilitating the selection of resilient varieties. This approach not only reduces potential economic losses but also minimizes the reliance on chemical control measures, promoting sustainable agricultural practices. The nutritional quality of lentils is a primary focus of breeding programs. Biofortification efforts can aim to increase the content of essential micronutrients, such as iron and zinc, in lentil grains, addressing global malnutrition issues. As a result, it's the need of the hour for the integration of modern genomic tools and traditional breeding methods which is essential for accelerating the development of improved lentil varieties that meet the demands of a growing global population and changing agricultural landscapes.

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