

# Review Article

## Advancements in Lentil Genomics for Enhanced Crop Breeding: A Review

---

### ABSTRACT

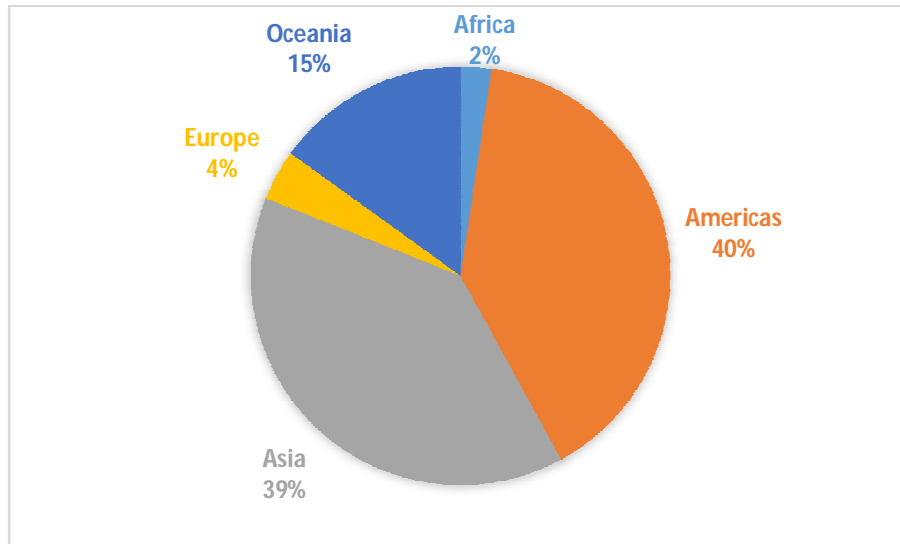
Lentil (*Lens culinaris* Medik) is an essential pulse crop that is widely grown for its high nutritional value, notably its high protein content, making it an important dietary component for vegetarians and vegans. Despite being the world's fifth most produced pulse, with large contributions from Canada and India, lentil production confronts obstacles such as poor productivity due to limited genetic improvement against biotic and abiotic stresses under rainfed cultivation conditions. Recent advances in lentil genetics and genomics, such as the discovery of genes related with yield, disease resistance, and nutritional content, have boosted breeding efforts to generate improved lentil varieties. The use of contemporary genomic techniques like molecular markers, marker-assisted selection (MAS), and next-generation sequencing (NGS) technology has sped up the discovery of quantitative trait loci (QTLs) and the production of novel cultivars with superior agronomic characteristics. Databases such as NCBI and ENA, as well as specialized resources like KnowPulse provide critical genomic data, while the creation of lentil genome assemblies, notably the CDC Redberry variety, has improved our understanding of lentil genetics. These resources help to solve the constraints of traditional breeding, particularly for complex characteristics impacted by genotype-environment interactions, opening the way for more robust and productive lentil varieties. The current study in lentil genomes, together with the development of enhanced genetic resources, has the potential to overcome production limits and improve worldwide lentil output and quality.

*Keywords: Genomics, Genomic Selection, GWAS, Lentil, Molecular Markers*

### 1. INTRODUCTION

The lentil plant, scientifically known as *Lens culinaris* Medik  $2n=2x=14$ , is a member of the Fabaceae family. It is a pulse crop that has been cultivated for thousands of years, making it one of the oldest known crops [1]. They are a staple in many cuisines around the world and are green alternative to animal meat protein [2]. It occupies fifth position in production worldwide among the pulses, with the production of 6.65 mt out of 5.5 mha areas; around 75% of the world's production is coming from Northern America and Asia (Figure 1). Canada and India being the largest and second largest producers with the total production of 2.3 MT and 1.26 MT, respectively [3]. Lentils are highly nutritious, rich in protein, fiber, vitamins, minerals and complex carbohydrates [4, 5, 6, 7]. They are an excellent source of plant-based protein, making them an important food source for vegetarians and vegans [2, 8]. Additionally, lentils are low in fat and glycemic index (GI), making them a healthy choice for those looking to maintain a balanced diet [9, 10]. Although there has been increase in the production of lentil over the period, the increase in productivity has not been realized [11]. This is due to poor genetic gain in lentil improvement [12]. However, the release of short-duration lentil varieties has gained areas under lentil cultivation in Bangladesh, Morocco, and Ethiopia [13]. Among other production constraints, lentils are being grown under rainfed conditions, and several biotic and abiotic stresses are associated with lower productivity [14, 15, 16, 17, 18, 19, 20]. There has been renewed interest in genetics of lentils in recent years [11, 13, 21]. Researchers have been studying the genetic makeup of different lentil varieties to identify genes linked with important traits such as yield, disease resistance, nutrient content and nutrient uptake [22, 23, 24, 25, 26]. This information can assist breeders in the development of enhanced lentil varieties that exhibit higher productivity, greater

resistance to diseases and pests, and superior nutritional characteristics. Moreover, progress in genomics research has enabled the creation of molecular markers that may be utilized in effective lentil breeding programs. Through the examination and comprehension of the genetic composition of lentils, breeders have the ability to generate novel cultivars that possess enhanced resistance against pests and diseases, as well as heightened nutritional content.



**Fig. 1. Production share of lentils by different regions of the world**

## **2. LENTIL GENOMICS: AN OVERVIEW**

Improving lentil genetics is essential for enhancing crop yield [27, 28, 29, 30, 31]. Although conventional breeding strategies have been able to enhance monogenic traits by combining and selecting desirable characteristics, they are not as efficient when it comes to improving seed yield. The main reason for this is primarily the intricate nature of polygenic inheritance and the interplay between genotype and environment. Initially, the main attention has been on important characteristics such as agronomic performance, drought, heat, cold, frost tolerance, seed quality, and resistance to several fungal diseases. Nevertheless, when it comes to quantitative characteristics that are significantly affected by environmental variables and genotype-environment interactions, conventional techniques have lower accuracy and require more time [12].

Integration of genomics into lentil improvement program is crucial for overcoming these constraints. Use of molecular markers in marker-assisted selection (MAS), marker-trait association analysis, genomic selection and genetic engineering provide more precise and effective ways to choose superior genotypes and introduce new genetic variation and genes into the cultivated gene pool [28, 32, 33, 34, 35].

The progress in molecular markers and genome-wide association studies (GWAS) has greatly enhanced our capacity to create precise genetic maps and identify crucial quantitative trait loci (QTLs)[22, 36, 37]. An essential aspect of implementing these contemporary methods is accurately identifying quantitative trait loci (QTLs) and strategically integrating them into desired cultivars. NGS technology has advanced our comprehension of genetic diversity by facilitating the sequencing of cultivars over a shorter period of time. Furthermore, the examination of the transcriptome under various situations has yielded more profound understanding of gene expression patterns. The progress made in this field has made it easier to identify quantitative trait loci (QTLs) and has resulted in the finding of several molecular markers, including simple sequence repeats (SSRs) and single nucleotide polymorphisms (SNPs).

These markers are crucial instruments for identifying cultivars with desirable characteristics, which in turn accelerates the advancement of more robust and productive types. By incorporating technologies such as MAS into breeding programs, the process of crop improvement becomes more efficient and focused, enabling the development of breeding methods that effectively meet the requirements of modern agriculture.

### 3. GENOMIC RESOURCES IN LENTIL

#### 3.1 DATABASES FOR GENES AND GENOMIC SEQUENCES IN LENTIL

There are various generic databases that cover datasets of various organisms, including Lentil, and are maintained by international communities or consortia and often publically funded. These databases, or consortia, are long-term sustainable; they work as archives for valuable data, and most of them are updated frequently, and the data stored in them can be retrieved freely. The repositories that contain datasets of lentil along with several other species include NCBI, ENA, DDBJ, Phytozome, Know Pulse and Pulse Crop Database. The details of these databases and archives are given in Table 1.

**Table 1: Databases for genes and genomic sequences in lentil**

S. No.	Database	URL	Description	Species	Data Type
1.	NCBI	<a href="https://www.ncbi.nlm.nih.gov/">https://www.ncbi.nlm.nih.gov/</a>	The National Center for Biotechnology Information promotes scientific and medical advancement by facilitating access to biomedical and genomic information	Lentil and other species across several kingdom	Gene, Protein, Genomic Sequences
2.	ENA	<a href="https://www.ebi.ac.uk/ena/">https://www.ebi.ac.uk/ena/</a>	The European Nucleotide Archive (ENA) offers a repository of global nucleotide sequencing data, encompassing raw sequencing datasets, sequence assembly, and functional annotation	Lentil and other species across several kingdom	Gene, Protein, Genomic Sequences
3.	DDBJ	<a href="https://www.ddbj.nig.ac.jp/">https://www.ddbj.nig.ac.jp/</a>	The DNA Data Bank of JapanCenter along with Bioinformatics offers data sharing and analysis services for life science research, contributing to the advancement of scientific knowledge	Lentil and other species across several kingdom	Gene, Protein, Genomic Sequences
4.	Phytozome	<a href="https://phytozome-next.jgi.doe.gov/">https://phytozome-next.jgi.doe.gov/</a>	Phytozome advance comparative genomics research by consolidating a vast assortment of plant genomes into one resource and performing thorough and consistent annotation and analysis, resulting in precise and informative findings	Lentil and other species	Genome Assembly and Annotation, Synteny
5	KnowPulse	<a href="https://knowpulse.usask.ca/">https://knowpulse.usask.ca/</a>	A website dedicated to providing comprehensive diversity data for the purpose of enhancing pulse crop development	Lentil and other legumes	Genome Assembly and Annotation
6	Pulse Crop Database	<a href="https://www.pulsedb.org/">https://www.pulsedb.org/</a>	Genome, Genetic and Breeding Recourses for Pulse crop Improvement	Lentil and other legumes	Genome Assembly and Annotation, QTL, Markers,

					and Traits
--	--	--	--	--	------------

Currently, there is no database available that covers only lentil, and if we compare the databases that can be used for lentil, there are only a few as compared to many other crops like rice and tomato. However, there is a possibility that new databases will incorporate more data once new genomics datasets are developed for lentil.

### 3.2 SEQUENCING PLATFORM FOR LENTIL GENOMICS

Rice was the first sequenced crop genome, which paved the way for the sequencing of several other crops, including the more complex one. The rice genome was sequenced through the Sanger sequencing method following a clone-by-clone approach and was a mammoth effort of the International Rice Genome Sequencing Project (IRGSP), which started in 1997 and took about 5 years to complete, mainly due to the limited output of the Sanger sequencing method and hardship involved. The advent of next-generation sequencing (NGS) or second generation sequencing technologies was driven by the demand for faster and more cost-effective methods to sequence vast amounts of genetic material. Over the years, a range of NGS platforms and techniques have been introduced, each utilizing distinct chemical processes and detection strategies. Despite their variations, all NGS technologies are characterized by their capacity for massively parallel processing, allowing the sequencing of thousands to millions of DNA fragments at once. This has made sequencing and re-sequencing very affordable and less time-consuming. Recent advancements in sequencing technologies have resulted in the emergence of Third Generation Sequencing (TGS) technologies, which have the ability to generate substantially longer reads compared to second-generation sequencing. These TGS technologies have found extensive use in genome research. The details of these sequencing technologies, which can also be used in lentil genomics, are given in Table 2.

**Table 2: Details of sequencing technologies used in genomics**

Sequencing Technology Generation	Chemistry	Methodology
1 <sup>st</sup> Generation	Chemical method (chain degradation) (Maxam and Gilbert method)	Chemical alteration of DNA followed by targeted cleavage at specific nucleotide bases
	Chain termination sequencing (Sanger method)	Targeted inclusion of labelled chain-terminating dideoxynucleotides (ddNTPs) during in vitro DNA replication
2 <sup>nd</sup> Generation	Pyrosequencing	Non-gel based DNA 'sequencing by synthesis' technique that uses light detection to detect inorganic pyrophosphate released during DNA synthesis
	Sequencing by synthesis	Incorporation of fluorescently labelled deoxyribonucleotide triphosphates (dNTPs) onto a replicating DNA strand in clusters

	Sequencing by ligation	DNA are sequenced by leveraging the mismatch sensitivity of the DNA ligase enzyme
3 <sup>rd</sup> Generation	Single Molecule Real Time (SMRT) sequencing by the use of Zero-Mode Waveguides (ZMW )	Single Molecule Real Time (SMRT) sequencing utilizes Zero-Mode Waveguides (ZMW) technology to separate the desired fluorescent signal from the intense background fluorescence produced by unincorporated free-floating nucleotides and requires no PCR amplification
	Sequencing by Binding	By using native nucleotides and eliminating the need to remove fluorescent modifications, the sequencing strand experiences minimal alterations, leading to more accurate base calls
	Nanopore sequencing	Uses flow cells with an array of small holes, known as nanopores, embedded in an electro-resistant membrane. Each nanopore detects the electric current passing through the nanopore and identify the specific nucleotide

Sequence datasets generated from NGS technologies have been widely used for the creation of genetic resources such as SSRs, EST-SSRs, and SNPs. These can be used for the development of physical maps, MAS, and GWAS. Moreover, the whole genome transcriptome analysis has resulted in the identification of genes upregulated and downregulated under various conditions or developmental stages. Novel transcript isoforms, gene fusion, and splice variants can also be identified from sequenced transcriptome assembly. Apart from these, various classes of non-coding RNAs, such as miRNAs, tRNAs, and lncRNAs, can also be detected and quantified using NGS technologies.

### 3.3 LENTIL GENOME ASSEMBLY

The initial version of the lentil genome assembly (The lentil genome assembly v1.0), based on the Canadian variety CDC Redberry, was released in January 2016. This assembly contains 7 pseudomolecules anchored by 6 high-density genetic linkage maps, accounting for about half of the 4.3 Gb lentil genome. The assembly was produced utilizing genomic and RNA sequencing data obtained by several institutions across the world using a variety of methods. The assembly, which includes identified potential genes, may be viewed with a genome browser (JBrowse) and accessible through the Knowpulse online portal (<http://knowpulse.usask.ca>) via BLAST searches.

Utilizing the power of next-generation sequencing, The Genome Assembly v2.0 of CDC Redberry lentil variety, which is accessible at [https://knowpulse.usask.ca/bio\\_data/2690904](https://knowpulse.usask.ca/bio_data/2690904), was constructed using long-read sequencing data, comprising 34x PacBio SMRT and 20x Oxford Nanopore reads. The assembly's contiguity was not only validated but also enhanced with the integration of HiC data, alongside both an optical and genetic map (LR-01; ILL 1704 x CDC Robin intraspecific RIL). The completed assembly totals 3.69 Gb, organized into 7 pseudo-molecules and 2,068 unplaced units.

## 4. USE OF LENTIL GENOMICS IN CROP IMPROVEMENT

### 4.1 MARKER TRAIT ASSOCIATION ANALYSIS

Conventional breeding is more effective in genetic improvement of traits with high heritability. Genetic gain of quantitative traits is low and very difficult in selection for traits governed by minor QTLs. With the advent of next-generation sequencing techniques, rapid identification of molecular markers linked with the genes, or QTLs, is possible. Higher genetic gain can be achieved for the traits governed by QTLs with small effect upon selection of traits using linked molecular markers. Genetic mapping utilizes both biparental mapping and association mapping, or genome-wide association studies (GWAS), to detect the genes or QTLs governing a trait. Biparental mapping restricts the genetic diversity between two parental lines and the limited number of recombination events. Alternatively, association mapping uses a large number of diverse parental lines; thus, it increases resolution, detects a large number of minor and major QTLs, and reduces the time spent developing mapping populations. Biparental mapping is extensively carried out in lentils for detection of QTLs of major traits including early plant vigor, heat tolerance, winter hardiness, salinity tolerance, nutritional and milling quality, disease resistance, and herbicide tolerance [32, 38, 39, 40, 41, 42, 43]. Grain yield remains a principal trait to breed on; thus, emphasis was given on increasing seed size of lentil. A number of genes governing seed size and weight were detected. Two QTLs for seed weight and seed size co-localized in the linkage group 4 explained phenotypic variance of 48.4% and 27.5%, respectively [44]. Breeding for these QTLs can improve simultaneously seed size and weight in lentils. Development of short-duration varieties in lentil is most suitable for the areas where the crop is grown after the harvest of rice. Delayed harvest of rice delays sowing of lentil; thus the crop suffers heat stress and diseases appear at later stages. Growing of short-duration varieties escapes the heat stress at the later growth stage and minimizes the yield loss in Indo-gangatic plains [45]. Shivaprasad et al. (2024) detected 11 loci for extra earliness in lentil; one InDel marker (I-SP-383.9) near the LcELF3a gene showed 82.35% PVE (phenotypic variation explained) for earliness [46]. A major flowering time locus was detected through biparental mapping on LG6; one of the SSR marker SSR212\_1 markers closely linked to the locus explained 57% of the PVE [47]. Targeting these genes in breeding programs would be useful in developing early-maturing genotypes. Diseases caused significant yield loss in lentils, and the use of environmentally hazardous chemicals to control the diseases also increased the production cost. Anthracnose can cause yield losses up to 70% under favorable conditions. Major fungal diseases are ascochyta blight (*Ascochyta lentis*), stemphyllium blight (*Stemphyllium botryosum*), aphanomyces root rot (*Aphanomyces euteiches*), and anthracnose caused by *Colletotrichum lentis* (Damm). Breeding for disease resistance in lentils through conventional breeding approaches achieved significant improvement. A small seeded lentil variety, "Pant Lentil 4" developed by pedigree selection, was high yielder, resistant to rust, wilt, and Ascochyta blight for North Western India [48]. A number of high-yielding varieties were developed in India, Africa, and Canada [49, 50]. Genomic regions governing resistance to Ascochyta blight [51, 52], stemphyllium blight [53], rust [54], anthracnose [55], and Fusarium wilt [56] were identified in Lentil. Genes conferring resistance to Ascochyta blight were detected in LG 1, 4, 5, and 9, accounting for up to 61% of PVE [51]. A major gene, LCt-2, has been designated for anthracnose resistance [57]. Recently, Gela et al. (2021) identified major resistance loci for anthracnose on linkage groups 3 and 7, accounting for 20.1–31.2% and 8.3–18.4% of variation, respectively [58]. Association mapping, also called LD (linkage disequilibrium) mapping, was effectively used for the detection of QTLs with high resolution in lentil. LD is a non-random association of loci present at different loci on the genome. LD between a trait and marker locus indicates association of the marker with the trait phenotype. Recently, genomic tools are being utilized to unlock the genetic potential of plant genetic resources for complex agronomic traits. Genome Wide Association Studies (GWAS) studies conducted using 96 diverse lentil genotypes detected one SSR (simple sequence repeats) PBALC 224 for seed diameter and two SSR, GLLC 614 and PBALC 29 for seed weight [59]. Lentil seed size and diameter are important parameters determining market class and price. More plump and round-shaped seeds have more efficiency of dehulling. Therefore, identification of the genomic region responsible for seed size,

diameter, and plumpness in lentil is useful for improving the trait. Major genomic regions for seed diameter are reported on LG 1, 2, and 7 [60, 61]. QTL clusters were detected using GWAS analysis on LG 1, 4, 5, 6, and 7 for root rot disease caused by *Aphanomyces euteiches* Drechs [24]. Utilization of global lentil germplasm to identify genotypes of important traits would assist the breeding process in realizing the fast genetic gain. One of the studies conducted using 196 ICARDA Reference Puls collection of lentils identified two flowering time loci on LG 3; eight loci for days to maturity on LG 2, 3, 5, 6, and 7; two loci for seed per pod on LG 2, and 7; and one locus on LG 1 [22]. A diverse panel of 96 lentil genotypes was used to map 24 QTLs with nine agronomic traits, including maturity, number of pods per plant, primary and secondary branches per plant and 100 seed yield [36]. QTLs detection can be affected by the environmental variations; GWAS applied in a population evaluated under a controlled environment can be most effective in the detection of QTLs. However, conducting a controlled environment may lead to improper judgment about the character expression under variable climatic conditions. Therefore, populations are tested over multiple seasons and locations. Under such circumstances, MetaGWAS has proved to be more effective than the standard to detect QTLs tested in multiple environments and having an unbalanced set of data. QTL detection through MetaGWAS analysis previously carried out in soybean [62], wheat [63], and canola [64]. Balech et al. (2024) recently used MetaGWAS analysis in lentil to detect herbicide tolerance and four SNPs detected to be linked with imazethapyr and metribuzin tolerance, which can be utilized in the development of herbicide tolerance lentil genotypes [32]. Biofortification is an important area of research in major food crops, including rice, wheat, maize, potatoes, and cassava. Enhancing the genetic potential of crops through which the grain mineral content increases and increasing their bioavailability is a sustainable approach to biofortification [65]. Inheritance of micronutrients is a complex trait and highly influenced by environmental fluctuation [45, 65, 66]. Lentil is a good source of minerals; large genetic variation for iron (Fe), zinc (Zn), and selenium (Se) was detected in the lentil germplasm [67]. Screening of lentil germplasm recorded grain iron concentrations ranging between 31.55 and 119.35 mg/kg, and that of grain Zn ranged from 7.80 to 75.45 mg/kg. Association mapping identified SSR markers PBALC 13, PBALC 206, and GLLC 563 linked with grain Fe concentration with 9% to 11% PVE and four SSR markers PBALC 353, SSR 317-1, PLC 62, and PBALC 217 linked with grain Zn concentration with 14% to 21% PVE [68]. Iron concentration in lentils is higher than in cereal crops [69]. Four QTL regions for Se concentration were identified in the LG 2 & 5, explaining phenotypic variation ranging from 6.3–16.9% [25]. For iron concentration, 21 QTLs were detected on six linkage groups (LG 1, 2, 4, 5, 6 & 7) explaining PVE of 5.9% to 14% [70]. In the recent past, twelve iron-rich biofortified lentil varieties developed at International Center for Agricultural Research in Dry Areas (ICARDA) were released by the Harvest Plus Programme in Syria, Nepal, India, and Bangladesh [71]. Varieties IPL 220 and L4704 were released in India with 89.10 [67] and 75 mg/kg concentrations of iron, respectively. Use of molecular markers and genomic tools would be effective in developing biofortified lentil varieties.

## 4.2 MARKER ASSISTED BREEDING

Molecular markers are among the genomic tools used on a large scale for crop improvement programs. Molecular markers tightly linked (5 cM) to the agronomic traits, disease resistance, and quality are available in lentils suitable for marker-assisted breeding (MAB), marker-assisted backcross (MABC), marker-assisted gene pyramiding, or genomic selection. A sizable number of PCR-based markers (RAPD, SSR, SRAP, etc.) that can detect easily with minimum cost and time are available to transfer the genes or QTLs through MAB or MABC in lentil. Tar'an et al. (2003) pyramided two genes, *ral1* and *AbR1*, to confer resistance to *Ascochyta* blight (*A. lentis*) and a major gene to confer resistance to anthracnose (*C. truncatum*) using RAPD markers: UBC 2271290 and RB18680 linked to *ral1* and *AbR1*, respectively, and OPO61250 linked to anthracnose resistance [72]. Successful gene introgression of anthracnose and *Stemphylium* blight disease resistance was reported from wild lentil *L. ervoides* in a lentil advanced backcross population developed in the background of cultivar CDC Redberry, which can be used further as valuable genetic resources for improvement of resistance to these diseases [73]. Unlike other crops, marker-assisted breeding in lentils is limited; most of the literature is confined to the use of molecular markers for genetic diversity analysis and detection of parental lines for specific traits. Marker-assisted gene or QTL introgression or pyramiding of biotic-abiotic stress tolerance and nutritional enhancing traits is relative higher in major field crops, particularly wheat, rice, and maize [74, 75, 76]. These could be attributable to the limited number of tightly linked markers (1.1 cM) identified with the target trait, the dearth of genomic data compared to the major cereals, and the less established infrastructure available for lentil breeders [77]. Recently,

genomic information in the pulses has increased significantly, which would lead to the detection of candidate genes and their fine mapping and marker-assisted selection.

### 4.3 GENOMIC SELECTION

MAS is the most effective method in plant breeding in selecting desirable plant types and making changes in phenotypes through the transfer of known genetic variations. However, economically important traits like yield, disease resistance, abiotic stress tolerance, nutrient use efficiency, and quality are governed by many genes, each accounting for a minor percentage of phenotypic variations. Selection of plants for minor QTLs in breeding programs is difficult; thus, it limits the MAS for QTLs with small effects. Under such circumstances, genomic selection (GS) based on genomic assisted breeding values (GEBVs) plays a significant role, where genome-wide markers are used to estimate the genomic potential of an individual genotype. GS involves developing genomic prediction equations using phenotyping and genotyping data of the training population, which is then used for predicting the GEBV of individual populations of a testing population that have not been phenotyped [78]. GS is more effective for the traits with low heritability, given more gain per unit time than the phenotypic selection and MAS [28]. GS can increase the higher genetic gain per unit time by phenotypic selection, shortening the generation interval in lentils [79]. Genetic gain was higher from selecting plants in early generations (F<sub>1</sub> or F<sub>2</sub>) than the later stages of segregating generations. During early generation selection, GS led to the loss of genetic diversity; however, the addition of additional phenotypes in F<sub>2</sub> families to the training populations can increase the GEBVs, genetic gain per, and decrease the rate of genetic diversity loss. Genomic prediction accuracy depends on several factors, including GxE interactions, inheritance of traits, and prediction models, which are important factors to be considered. The advantage of GS is that it accounts for GxE interactions effectively, thus allowing in selecting genotypes for the untested environments. GP methods like ridge regression, Bayesian LASSO, BayesA, BayesB, kernel-based approaches, and genomic BLUP models have been used. Prediction accuracy of GEBVs was recorded higher (0.34-0.83) than the BLUP estimated breeding values (EBVs) (0.22-0.54) in lentil [28]. Moderate to high prediction accuracy was observed for grain yield (0.47-0.57), Ascochyta blight (0.45-0.64), Botrytis grey mold (0.63), boron tolerance (0.47 to 0.72), and salt tolerance (0.39 to 0.52) [28]. Moderately higher prediction accuracy indicated the effectiveness of GS in improving these traits in lentil. Another study reported that BayesB has the highest prediction accuracy for traits controlled by few QTLs with relatively large effects, while incorporation of genotype-environment interactions improved prediction accuracy by up to 66% [80]. Moderate to high prediction accuracy within population (range of 0.36– 0.85) and across-environment (range of 0.19– 0.89), which were higher than the across-population prediction suggesting implementation of GS in lentil to predict both within population and across the environment.

## 5. GENETIC ENGINEERING AND GENOME EDITING

Transgenic approach has facilitated the transfer of useful genes across the gene pool in lentil through transformation. The introduction of new genes has been generally done through particle bombardment and *Agrobacterium tumefaciens* infection method. With the advancement of sequencing techniques, adequate information about the whole genome sequence is available in sequence databases which can be used to develop transgenic plants to improve the lentil. Report is available for transformation of lentil via number of explants viz. shoot apices, epicotyl, root, cotyledons and cotyledonary nodes [81]. Particle bombardment technique was used to produce first transient and stable expression in cotyledonary tissues [82]. An herbicide resistant lentil was developed using *Agrobacterium* mediated transformation containing bar gene as selectable marker [83]. Lentil was also transformed with the DREBA gene (derived by rd29A promoter) into lentil for enhancing drought and salinity tolerance [35]. A study reported transformation of two microsperma seeded lentil varieties namely Bari Masur-4 and Bari Masur-5 in Bangladesh using *A. tumefaciens* strain LBA4404 [84]. Though, genome editing has been used towards improvement of various crops, there is no report available for lentil. However, genome editing may be an efficient choice to improve the lentil for various agronomical traits and mitigation of various biotic and abiotic stresses.

## 6. CONCLUSION

Advances in lentil genomes have considerably helped to overcome the constraints of traditional breeding, notably in terms of poor production, vulnerability to biotic and abiotic stressors, and the restrictions of rainfed farming. The use of contemporary genomic technologies, including as molecular

markers, marker-assisted selection, and next-generation sequencing, has hastened the discovery of critical genes and quantitative trait loci (QTLs) linked to yield, disease resistance, and nutritional content. This innovation has permitted the introduction of superior lentil varieties with improved agronomic features, resulting in increased worldwide lentil output and quality.

## 7. FUTURE PROSPECTUS

Future opportunities for lentil research include increased examination of genomic resources to better understand the genetic basis of complex features like drought tolerance and nutrient efficiency. The use of gene editing technologies like as CRISPR/Cas9 has the potential to produce lentil varieties with customized features by precisely modifying certain genes. Furthermore, incorporating phenomics, bioinformatics, and machine learning into breeding projects may result in more efficient selection procedures and the creation of climate-resilient lentil varieties. As genetic data becomes more abundant, worldwide collaboration and data sharing will be critical for driving lentil development and guaranteeing food security in the face of global problems like climate change, population expansion and malnutrition.

## REFERENCES

1. <https://www.icarda.org/media/blog/lentil-ICARDA-India#:~:text=ICARDA%20is%20grateful%20to%20Indian,supporting%20ICARDA's%20work%20on%20Lentils.&text=Lentil%2C%20a%20crop%20that%20ICARDA,India's%20food%20security%20and%20economy.>
2. Brishti FH, Mzek T, Saari N, Rifna EJ, Dwivedi M, Kaur K et al. Lentil Protein: A Sustainable and Green Alternative to Animal Meat Protein. In: Ahmed J, Siddiq M, Uebersax MA, editors. Lentils: Production, Processing Technologies, Products, and Nutritional Profile: Wiley; 2023. p. 203-35.
3. <https://www.fao.org/statistics/en>.
4. Khan AR, Alam S, Ali S, Bibi S, Khalil IA. Dietary fiber profile of food legumes. Sarhad J. Agric. 2007;23(3):763.
5. Dhull SB, Kinabo J, Uebersax MA. Nutrient profile and effect of processing methods on the composition and functional properties of lentils (*Lens culinaris* Medik): A review. Legum. sci. 2022;5(1):e156.
6. Joshi M, Timilsena Y, Adhikari B. Global production, processing and utilization of lentil: A review. J. Integr. Agric. 2017;16(12):2898-913.
7. Chelladurai V, Erkinbaev C. Lentils. In: Manickavasagan A, Thirunathan P, editors. Pulses: Processing and Product Development: Springer; 2020. p. 129-43.
8. Stefaniak TR, McPhee KE. Lentil. In: Ron AMD, editor. Grain Legumes: Springer; 2015. p. 111-40.
9. Urbano G, Porres JM, Frías J, Vidal-Valverde C. Nutritional value. In: Yadav SS, McNeil DL, Stevenson PC, editors. Lentil: An ancient crop for modern times: Springer; 2007. p. 47-93.
10. <https://www.lentils.org/health-nutrition/nutritional-information/>.
11. Tiwari M, Singh B, Min D, Jagadish SK. Omics path to increasing productivity in less-studied crops under changing climate—lentil a case study. Front. Plant Sci. 2022;13:813985.
12. Kumar S, Ali M. GE interaction and its breeding implications in pulses. The Botanica. 2006;56:31-6.
13. Kumar J, Sen Gupta D, Baum M, Varshney RK, Kumar S. Genomics-assisted lentil breeding: Current status and future strategies. Legum. sci. 2021;3(3):e71.
14. Paudel GP, Devkota M, Keil A, McDonald AJ. Climate and landscape mediate patterns of low lentil productivity in Nepal. Plos one. 2020;15(4):e0231377.
15. Sehgal A, Sita K, Rehman A, Farooq M, Kumar S, Yadav R et al. Lentil. In: Sadras VO, Calderini DF, editors. Crop physiology case histories for major crops: Elsevier; 2021. p. 408-28.

16. Sita K, Sehgal A, Kumar J, Kumar S, Singh S, Siddique KH et al. Identification of high-temperature tolerant lentil (*Lens culinaris* Medik.) genotypes through leaf and pollen traits. *Front. Plant Sci.* 2017;8:744.
17. Junior MdAL, Lima A, Arruda J, Smith D. Effect of root temperature on nodule development of bean, lentil and pea. *Soil Biol. Biochem.* 2005;37(2):235-9.
18. Maqbool A, Shafiq S, Lake L. Radiant frost tolerance in pulse crops—a review. *Euphytica.* 2010;172:1-12.
19. Mishra BK, Srivastava JP, Lal JP. Drought stress resistance in two diverse genotypes of lentil imposed at different phenophases. *J. Food Legumes.* 2014;27(4):307-14.
20. Singh N, Singh G. Response of lentil (*Lens culinaris* Medikus) to phosphorus-A review. *Agricultural Reviews.* 2016;37(1):27-34.
21. Kumar J, Sen Gupta D. Prospects of next generation sequencing in lentil breeding. *Mol. Biol. Rep.* 2020;47(11):9043-53.
22. Rajendran K, Coyne CJ, Zheng P, Saha G, Main D, Amin N et al. Genetic diversity and GWAS of agronomic traits using an ICARDA lentil (*Lens culinaris* Medik.) Reference Plus collection. *Plant Genet. Res.* 2021;19(4):279-88.
23. Dadu RHR, Bar I, Ford R, Sambasivam P, Croser J, Ribalta F et al. *Lens orientalis* contributes quantitative trait loci and candidate genes associated with ascochyta blight resistance in lentil. *Front. Plant Sci.* 2021;12:703283.
24. Ma Y, Marzougui A, Coyne CJ, Sankaran S, Main D, Porter LD et al. Dissecting the genetic architecture of aphanomyces root rot resistance in lentil by QTL mapping and genome-wide association study. *Int. J. Mol. Sci.* 2020;21(6):2129.
25. Ates D, Sever T, Aldemir S, Yagmur B, Temel HY, Kaya HB et al. Identification QTLs controlling genes for Se uptake in lentil seeds. *PLoS one.* 2016;11(3):e0149210.
26. Singh B, Singh S, Mahato AK, Dikshit HK, Tripathi K, Bhatia S. Delineation of novel genomic loci and putative candidate genes associated with seed iron and zinc content in lentil (*Lens culinaris* Medik.). *Plant Sci.* 2023;335:111787.
27. Shahwar D, Ansari M, Khatoon B, Park Y. Phenotypic characterization of ethyl methanesulfonate (EMS)-induced bigger pod (bp) with multiple seed mutants in lentil (*Lens culinaris*). *Biocatal. Agric. Biotechnol.* 2024:103259.
28. Gebremedhin A, Li Y, Shunmugam AS, Sudheesh S, Valipour-Kahrood H, Hayden MJ et al. Genomic selection for target traits in the Australian lentil breeding program. *Front. Plant Sci.* 2024;14:1284781.
29. Wani MR, Laskar RA, Raina A, Khan S, Khan TU. Application of chemical mutagenesis for improvement of productivity traits in lentil (*Lens culinaris* Medik). *Ann. Biol.* 2021;37(1):69-75.
30. Singh S, Singh I, Gill R, Kumar S, Sarker A. Genetic studies for yield and component characters in large seeded exotic lines of lentil. *J. Food Legumes.* 2009;22(4):229-32.
31. Sarker A, Aydogan A, Chandra S, Kharrat M, Sabaghpour S. Genetic enhancement for yield and yield stability. In: Erskine W, Muehlbauer FJ, Sarker A, Sharma B, editors. *The lentil: botany, production and uses*: CABI Wallingford UK; 2009. p. 102-20.
32. Balech R, Maalouf F, Kaur S, Jighly A, Joukhadar R, Alsamman AM et al. Identification of novel genes associated with herbicide tolerance in Lentil (*Lens culinaris* ssp. *culinaris* Medik.). *Sci. Rep.* 2024;14(1):10215.
33. Solanki R, Singh S, Kumar J. Molecular marker assisted testing of hybridity of F1 plants in lentil. *J. Food Legumes.* 2010;23(1):21-4.
34. Mbasani-Mansi J, Ennami M, Briache FZ, Gaboun F, Benbrahim N, Triqui ZEA et al. Characterization of genetic diversity and population structure of Moroccan lentil cultivars and landraces using molecular markers. *Physiol. Mol. Biol. Plants.* 2019;25(4):965-74.
35. Khatib F, Makris A, Yamaguchi-Shinozaki K, Kumar S, Sarker A, Erskine W et al. Expression of the DREB1A gene in lentil (*Lens culinaris* Medik. subsp. *culinaris*) transformed with the *Agrobacterium* system. *Crop Pasture Sci.* 2011;62(6):488-95.
36. Kumar J, Gupta S, Gupta DS, Singh NP. Identification of QTLs for agronomic traits using association mapping in lentil. *Euphytica.* 2018;214:1-15.
37. Tullu A, Tar'an B, Warkentin T, Vandenberg A. Construction of an intraspecific linkage map and QTL analysis for earliness and plant height in lentil. *Crop sci.* 2008;48(6):2254-64.

38. Mane R, Katoch M, Singh M, Sharma R, Sharma T, Chahota R. Identification of genomic regions associated with early plant vigour in lentil (*Lens culinaris*). J.Genet. 2020;99(1):21.
39. Singh D, Singh CK, Singh Tomar RS, Pal M. Genetics and molecular mapping of heat tolerance for seedling survival and pod set in lentil. Crop Sci. 2017;57(6):3059-67.
40. Kahraman A, Kusmenoglu I, Aydin N, Aydogan A, Erskine W, Muehlbauer FJ. QTL mapping of winter hardiness genes in lentil. Crop Sci. 2004;44(1):13-22.
41. Subedi M, Bett KE, Khazaee H, Vandenberg A. Genetic mapping of milling quality traits in lentil (*Lens culinaris* Medik.). Plant genome. 2018;11(2):170092.
42. Sudheesh S, Rodda MS, Davidson J, Javid M, Stephens A, Slater AT et al. SNP-based linkage mapping for validation of QTLs for resistance to ascochyta blight in lentil. Front. Plant Sci. 2016;7:1604.
43. Singh D, Singh CK, Tomar RSS, Sharma S, Karwa S, Pal M et al. Genetics and molecular mapping for salinity stress tolerance at seedling stage in lentil (*Lens culinaris* Medik.). Crop Sci. 2020;60(3):1254-66.
44. Verma P, Goyal R, Chahota R, Sharma TR, Abdin M, Bhatia S. Construction of a genetic linkage map and identification of QTLs for seed weight and seed size traits in lentil (*Lens culinaris* Medik.). PloS one. 2015;10(10):e0139666.
45. Narendra M, Chandan R, Sudhir K, Parminder V, Nitish D. Effect of terminal heat stress on physiological traits, grain zinc and iron content in wheat (*Triticum aestivum* L.). Czech J Genet Plant Breed. 2021;57(2):47-50.
46. Shivaprasad KM, Dikshit HK, Mishra GP, Sinha SK, Aski M, Kohli M et al. Delineation of loci governing an extra-earliness trait in lentil (*Lens culinaris* Medik.) using the QTL-Seq approach. Plant Biotechnology J. 2024.
47. Kahrman A, Temel HY, Aydogan A, Tanyolac MB. Major quantitative trait loci for flowering time in lentil. Turk. J. Agric. For. 2015;39(4):588-95.
48. Singh I, Singh J, Singh A, Chauhan M. Pant Lentil 4: a high yielding, rust-, wilt-and blight-resistant variety for the North-Western Plains of India. LENS Newsletter. 1994;21(1):8-9.
49. <https://www.seednet.gov.in/>.
50. Tekalign A, Tadesse T, Asmare B. Lentil Variety Development for Yield and Disease Resistance for Potential Areas: Registration of a Lentil Variety Named Debine. Comput. Biol. Bioinform. 2022;10(1):9-13.
51. Gupta D, Taylor P, Inder P, Phan H, Ellwood S, Mathur P et al. Integration of EST-SSR markers of *Medicago truncatula* into intraspecific linkage map of lentil and identification of QTL conferring resistance to ascochyta blight at seedling and pod stages. Mole. Breed. 2012;30:429-39.
52. Polanco C, Sáenz de Miera LE, González AI, García P, Fratini R, Vaquero F et al. Construction of a high-density interspecific (*Lens culinaris* x *L. odemensis*) genetic map based on functional markers for mapping morphological and agronomical traits, and QTLs affecting resistance to Ascochyta in lentil. PloS one. 2019;14(3):e0214409.
53. Saha GC, Sarker A, Chen W, Vandemark GJ, Muehlbauer FJ. Inheritance and linkage map positions of genes conferring resistance to stemphylium blight in lentil. Crop Sci. 2010;50(5):1831-9.
54. Dikshit H, Singh A, Singh D, Aski M, Jain N, Hegde V et al. Tagging and mapping of SSR marker for rust resistance gene in lentil (*Lens culinaris* Medikus subsp. *culinaris*). Indian J. Exp. Biol. 2016;54(6):394-9.
55. Bhadauria V, Bett KE, Zhou T, Vandenberg A, Wei Y, Banniza S. Identification of *Lens culinaris* defense genes responsive to the anthracnose pathogen *Colletotrichum truncatum*. BMC Genet. 2013;14:1-9.
56. Hamwieh A, Udupa SM, Choumane W, Sarker A, Dreyer F, Jung C et al. A genetic linkage map of *Lens* sp. based on microsatellite and AFLP markers and the localization of fusarium vascular wilt resistance. Theor. Appl. Genet. 2005;110:669-77.
57. Tullu A, Buchwaldt L, Warkentin T, Taran B, Vandenberg A. Genetics of resistance to anthracnose and identification of AFLP and RAPD markers linked to the resistance gene in PI 320937 germplasm of lentil (*Lens culinaris* Medikus). Theor. Appl. Genet. 2003;106:428-34.

58. Gela TS, Koh CS, Caron CT, Chen L-A, Vandenberg A, Bett KE. QTL mapping of lentil anthracnose (*Colletotrichum lentis*) resistance from *Lens ervoides* accession IG 72815 in an interspecific RIL population. *Euphytica*. 2021;217:1-11.
59. Singh A, Dikshit H, Mishra G, Aski M, Kumar S. Association mapping for grain diameter and weight in lentil using SSR markers. *Plant Gene*. 2019;20:100204.
60. Fedoruk MJ, Vandenberg A, Bett KE. Quantitative trait loci analysis of seed quality characteristics in lentil using single nucleotide polymorphism markers. *Plant Genome*. 2013;6(3):plantgenome2013.05.0012.
61. Khazaei H, Fedoruk M, Caron CT, Vandenberg A, Bett KE. Single nucleotide polymorphism markers associated with seed quality characteristics of cultivated lentil. *Plant genome*. 2018;11(1):170051.
62. Shook JM, Zhang J, Jones SE, Singh A, Diers BW, Singh AK. Meta-GWAS for quantitative trait loci identification in soybean. *G3-Genes Genom Genet*. 2021;11(7):jkab117.
63. Battenfield SD, Sheridan JL, Silva LD, Miclaus KJ, Dreisigacker S, Wolfinger RD et al. Breeding-assisted genomics: Applying meta-GWAS for milling and baking quality in CIMMYT wheat breeding program. *PLoS One*. 2018;13(11):e0204757.
64. Fikere M, Barbulescu D, Malmberg MM, Spangenberg GC, Cogan NO, Daetwyler HD. Meta-analysis of GWAS in canola blackleg (*Leptosphaeria maculans*) disease traits demonstrates increased power from imputed whole-genome sequence. *Sci. Rep*. 2020;10(1):14300.
65. Roy C, Kumar S, Ranjan RD, Kumhar SR, Govindan V. Genomic approaches for improving grain zinc and iron content in wheat. *Front. Genet*. 2022;13:1045955.
66. Gupta S, Das S, Dikshit HK, Mishra GP, Aski MS, Bansal R et al. Genotype by environment interaction effect on grain iron and zinc concentration of Indian and mediterranean lentil genotypes. *Agronomy*. 2021;11(9):1761.
67. Kumar J, Mir RR, Dutta A, Singh A, Kumar V, Tyagi S et al. Estimation of iron, zinc, phytic acid concentration and protein content in lentil seeds over locations and their marker-trait association analysis. *J. Food Compos. Anal*. 2024;127:105999.
68. Singh A, Sharma V, Dikshit HK, Aski M, Kumar H, Thirunavukkarasu N et al. Association mapping unveils favorable alleles for grain iron and zinc concentrations in lentil (*Lens culinaris* subsp. *culinaris*). *PLoS One*. 2017;12(11):e0188296.
69. Roy C, Kumar R, Ranjan RD, Virk P. Response of elite biofortified wheat genotypes for grain zinc and iron concentration with and without zinc application. *Vegetos*. 2024:1-9.
70. Aldemir S, Ateş D, TEMEL HY, Yağmur B, Alsaleh A, Kahriman A et al. QTLs for iron concentration in seeds of the cultivated lentil (*Lens culinaris* Medic.) via genotyping by sequencing. *Turk. J. Agric. For*. 2017;41(4):243-55.
71. <https://www.harvestplus.org/crop/iron-zinc-lentil/>.
72. Tar'an B, Buchwaldt L, Tullu A, Banniza S, Warkentin T, Vandenberg A. Using molecular markers to pyramid genes for resistance to ascochyta blight and anthracnose in lentil (*Lens culinaris* Medik). *Euphytica*. 2003;134:223-30.
73. Gela TS, Adobor S, Khazaei H, Vandenberg A. An advanced lentil backcross population developed from a cross between *Lens culinaris* × *L. ervoides* for future disease resistance and genomic studies. *Plant Genet. Res*. 2021;19(2):167-73.
74. Das G, Patra JK, Baek K-H. Insight into MAS: a molecular tool for development of stress resistant and quality of rice through gene stacking. *Front. Plant Sci*. 2017;8:985.
75. Saini VK, Roy C, Prasad P. Effectiveness of *Lr34* gene in reducing leaf rust severity in wheat cultivar BRW 934 transferred through marker-assisted backcross. *Eur. J. Plant Pathol*. 2024;169:601-10.
76. Prasanna BM, Palacios-Rojas N, Hossain F, Muthusamy V, Menkir A, Dhliwayo T et al. Molecular breeding for nutritionally enriched maize: status and prospects. *Front. Genet*. 2020;10:1392.
77. Kumar J, Choudhary AK, Solanki RK, Pratap A. Towards marker-assisted selection in pulses: a review. *Plant Breed*. 2011;130(3):297-313.
78. Juliana P, He X, Poland J, Roy KK, Malaker PK, Mishra VK et al. Genomic selection for spot blotch in bread wheat breeding panels, full-sibs and half-sibs and index-based selection for spot blotch, heading and plant height. *Theor. Appl. Genet*. 2022;135(6):1965-83.

79. Li Y, Kaur S, Pembleton LW, Valipour-Kahrood H, Rosewarne GM, Daetwyler HD. Strategies of preserving genetic diversity while maximizing genetic response from implementing genomic selection in pulse breeding programs. *Theor. Appl. Genet.* 2022;135(6):1813-28.
80. Haile TA, Heidecker T, Wright D, Neupane S, Ramsay L, Vandenberg A et al. Genomic selection for lentil breeding: Empirical evidence. *Plant Genome.* 2020;13(1):e20002.
81. Sarker R, Mustafa BM, Biswas A, Mahbub S, Nahar M, Hashem R et al. In vitro regeneration in lentil (*Lens culinaris* Medik.). *Plant Tissue Cult.* 2003;13(2):155-63.
82. Öktem H, Mahmoudian M, Eyidođan F, Yücel M. GUS gene delivery and expression in lentil cotyledonary nodes using particle bombardment. *Lens Newsletter.* 1999;26(1/2):3-6.
83. Khatib F, Koudsieh S, Ghazal B, Barton J, Tsujimoto H, Baum M. Developing herbicide resistant lentil (*Lens culinaris* Medikus subsp. *culinaris*) through Agrobacterium mediated transformation. *Arab J. Plant Prot.* 2007;25(2):185-92.
84. Das SK, Shethi KJ, Hoque M, Sarker R. Agrobacterium-mediated genetic transformation in lentil (*Lens culinaris* Medik.) followed by in vitro flowering and seed formation. *Plant Tissue Cult. Biotechnol.* 2012;22(1):13-26.

UNDER PEER REVIEW