The Genetics of Root Architecture in Legumes: Implications for Nutrient Uptake Efficiency

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Abstract This study aims to explore the genetic determinants of root architecture in legumes and their implications for nutrient uptake efficiency. By examining various genetic traits and mechanisms, the study seeks to provide a comprehensive understanding of how root system development influences nutrient acquisition in legume crops. The study identifies several key genetic traits and mechanisms that significantly influence root system architecture (RSA) and nutrient uptake in legumes. Notable traits include root length, root branching, root diameter, and root proliferation rate, which are genetically defined and can enhance water and nutrient uptake under stress conditions. Genome-wide association studies (GWAS) have revealed significant single nucleotide polymorphisms (SNPs) and quantitative trait loci (QTLs) associated with these root traits, providing insights into the genetic architecture of legume roots. Advances in high-throughput phenotyping and omics approaches have further facilitated the dissection of genomic, proteomic, and metabolomic structures of these traits, aiding in the development of drought-tolerant and nutrient-efficient cultivars. Understanding the genetic basis of root architecture in legumes is crucial for improving crop cultivation and nutrient efficiency. By identifying and utilizing beneficial genetic variations, breeders can develop legume varieties with optimized root systems that enhance water and nutrient uptake, thereby improving yield and resilience under various environmental conditions. This knowledge is pivotal for addressing food security challenges and promoting sustainable agricultural practices.

Keywords Legumes; Root architecture; Genetic traits; Nutrient uptake; Crop efficiency

1 Introduction

Root architecture in legumes is a critical determinant of plant health and productivity, particularly under stress conditions such as drought and nutrient deficiency. The root system architecture (RSA) encompasses various traits including root length, root hairs, root branching, root diameter, and root proliferation rate, all of which are genetically defined and can significantly influence water and nutrient uptake efficiency (Ye et al., 2018). Given the increasing occurrence of extreme weather patterns due to climate change, understanding and improving RSA in legumes is essential for enhancing crop resilience and ensuring food security (Chen et al., 2023).

Legumes are a vital component of human and animal diets due to their unique nutritional composition and their ability to fix atmospheric nitrogen through root nodule symbiosis with rhizobia. This symbiotic relationship not only improves soil fertility but also reduces the need for synthetic nitrogen fertilizers, making legumes an important crop for sustainable agriculture (Sharma et al., 2020). However, the productivity of legumes is often hampered by environmental stresses such as drought and phosphorus deficiency, which can severely limit their growth and yield (Chen et al., 2023).

This study synthesizes current knowledge on the genetics of root architecture in legumes and its implications for nutrient uptake efficiency. It summarizes the genetic diversity and quantitative trait loci (QTLs) associated with root system architecture (RSA) in major legume crops, providing insights into how these traits can be manipulated to improve water and nutrient uptake under stress conditions. The study discusses the role of advanced phenotyping and omics technologies in identifying key genes and regulatory networks involved in root development and stress responses. It also highlights strategies for improving phosphorus acquisition efficiency (PAE) and drought tolerance through root trait modification, emphasizing traits like root length, root hairs, and

root branching. Additionally, it explores the potential of root-microbe interactions in enhancing legume resistance to root diseases. By integrating findings from various studies, this research aims to offer a comprehensive understanding of the genetic and molecular mechanisms underlying root architecture in legumes, aiding in the development of legume varieties with optimized root systems for better nutrient uptake efficiency and stress resilience, thus contributing to sustainable agriculture and food security.

2 Fundamentals of Root Architecture in Legumes

2.1 Definition and components of root architecture

Root architecture refers to the spatial configuration of a plant's root system, encompassing the arrangement, structure, and distribution of roots within the soil. Key components of root architecture include root length, root surface area, root volume, root diameter, and the number of root tips and forks. These traits collectively influence the plant's ability to acquire water and nutrients from the soil, which is crucial for growth and productivity, especially under stress conditions such as drought or nutrient deficiency (Ye et al., 2018).

2.2 Root development stages and growth patterns

Root development in legumes occurs through distinct stages, starting from the embryonic root (radicle) that emerges during germination, followed by the formation of primary, lateral, and adventitious roots. The growth patterns of these roots are influenced by genetic and environmental factors, which determine their length, branching, and overall architecture. Studies have shown that root traits such as total root length, surface area, and volume are critical for efficient water and nutrient uptake, particularly under stress conditions like drought and low phosphorus availability (Priya et al., 2021). Additionally, the temporal genetic patterns of root growth reveal the existence of both persistent and stage-specific genetic factors that control root development, highlighting the dynamic nature of root architecture (Wang et al., 2019).

2.3 Differences in root architecture among legume species

Legume species exhibit significant variability in root architecture, which is influenced by their genetic makeup and adaptation to different environmental conditions. For instance, lentil (*Lens culinaris*) genotypes show considerable variation in root traits such as total root length, surface area, and root volume, which correlate with their drought tolerance. Similarly, mungbean (*Vigna radiata*) genotypes display differences in root architectural traits under normal and low phosphorus conditions, with certain genotypes showing superior root traits that enhance phosphorus uptake efficiency. Comparative studies in pea (*Pisum sativum*) have identified genetic loci associated with both root architecture and resistance to root pathogens, indicating that root traits can be leveraged to improve disease resistance and overall plant health (Reddy et al., 2019). These differences underscore the importance of understanding and utilizing genetic diversity in root architecture to enhance nutrient uptake efficiency and stress tolerance in legumes (Wang et al., 2018).

3 Genetic Basis of Root Architecture in Legumes

3.1 Key genes involved in root development and architecture

Root system architecture (RSA) in legumes is influenced by a variety of genes that regulate different aspects of root growth and development. For instance, the transcription factor NODULE INCEPTION (NIN) in Lotus japonicus is essential for initiating cortical cell divisions during nodulation and also regulates the gene ASYMMETRIC LEAVES 2-LIKE 18/LATERAL ORGAN BOUNDARIES DOMAIN 16a (ASL18/LBD16a), which is required for lateral root development. Additionally, genome-wide association studies (GWAS) in mungbean have identified several single nucleotide polymorphisms (SNPs) associated with phosphorus use efficiency traits, which are crucial for root architectural development under low-phosphorus conditions. In *Arabidopsis thaliana*, genes involved in lateral root development and auxin signaling pathways have been associated with RSA traits, highlighting the genetic complexity underlying root architecture (Deja-Muylle et al., 2022).

3.2 Genetic pathways and molecular mechanisms

The genetic pathways and molecular mechanisms governing root architecture in legumes involve intricate signaling networks. For example, the NIN transcription factor in *Lotus japonicus* not only regulates nodule organogenesis but also incorporates a lateral root developmental pathway downstream to drive nodule symbiosis. This indicates a shared genetic pathway between lateral root development and root nodule formation. In mungbean, the genetic basis of phosphorus use efficiency traits has been linked to specific SNPs that regulate nutrient uptake and root architectural development pathways. Furthermore, the genetic variability in root traits under different environmental conditions, such as drought and phosphorus deficiency, underscores the role of genetic pathways in adapting root architecture to optimize nutrient uptake and water use efficiency (Reddy et al., 2019).

3.3 Genetic variation and heritability of root traits

Genetic variation and heritability of root traits are critical for breeding programs aimed at improving root architecture in legumes. Studies have shown significant genetic variability in root traits among different legume genotypes. For instance, in mungbean, significant variations and medium to high heritability were observed for root architectural traits under normal and low phosphorus conditions, indicating the potential for genetic improvement. Similarly, in lentil, significant variation in root traits was reported in response to drought stress, with certain genotypes showing higher drought tolerance based on root length, surface area, and volume (Priya et al., 2021). The heritability of these traits suggests that they can be effectively selected for in breeding programs to enhance nutrient uptake efficiency and stress tolerance in legumes (Soyano et al., 2019).

4 Environmental Influence on Root Architecture

4.1 Interaction between genetics and environmental factors

The root architecture of legumes is significantly influenced by the interaction between genetic factors and environmental conditions. Genetic diversity in root system architecture (RSA) plays a crucial role in plant adaptation to various environmental stresses, such as drought. For instance, genetic variations in root traits, such as root length, root diameter, and root proliferation rate, have been identified as key factors in enhancing water capture and use efficiency in grain legumes under drought conditions (Priya et al., 2021). High-throughput phenotyping techniques have facilitated the screening of legume germplasm for these traits, enabling the development of drought-tolerant cultivars. Additionally, the integration of genetic and genomic approaches has been pivotal in dissecting the molecular processes that govern RSA, thereby aiding in the improvement of legume productivity under water-limited environments (Ye et al., 2018).

4.2 Role of soil type, moisture, and nutrient availability

Soil type, moisture levels, and nutrient availability are critical environmental factors that shape the root architecture of legumes. Different soil types can influence root traits such as root length, root hair width, and root diameter, which in turn affect nutrient uptake efficiency. For example, in low-phosphorus soils, legumes like *Aspalathus linearis* exhibit greater phosphorus acquisition traits, including specific root length and root hair width, which enhance their phosphorus uptake efficiency (MacAlister et al., 2018). Moisture availability also plays a significant role; under drought conditions, legumes with deeper and more proliferative root systems are better equipped to extract water and nutrients, thereby improving their drought tolerance and yield. Furthermore, nutrient availability, particularly nitrogen and phosphorus, can influence root architecture and the allocation of carbon to root symbionts, such as mycorrhizal fungi and rhizobia, which are essential for nutrient uptake and overall plant health (Zinta et al., 2022).

4.3 Stress conditions (drought, salinity) and root adaptation mechanisms

Legumes exhibit various root adaptation mechanisms in response to stress conditions such as drought and salinity. Drought stress, in particular, has been shown to significantly impact root traits, leading to adaptations that enhance water and nutrient uptake. For instance, under drought conditions, legumes develop deeper and more extensive root systems, which help in accessing water from deeper soil layers (Figure 1) (Blessing et al., 2018). Additionally,

traits such as low stomatal conductance and improved photosynthetic capacity are beneficial under terminal drought conditions, helping to maintain soil moisture until the critical pod-filling period. Salinity stress also affects root architecture, with legumes adapting by altering root traits to improve salt tolerance and maintain nutrient uptake8. Understanding these adaptation mechanisms is crucial for developing legume cultivars that can withstand environmental stresses and ensure sustainable agricultural productivity (Nadeem et al., 2019).
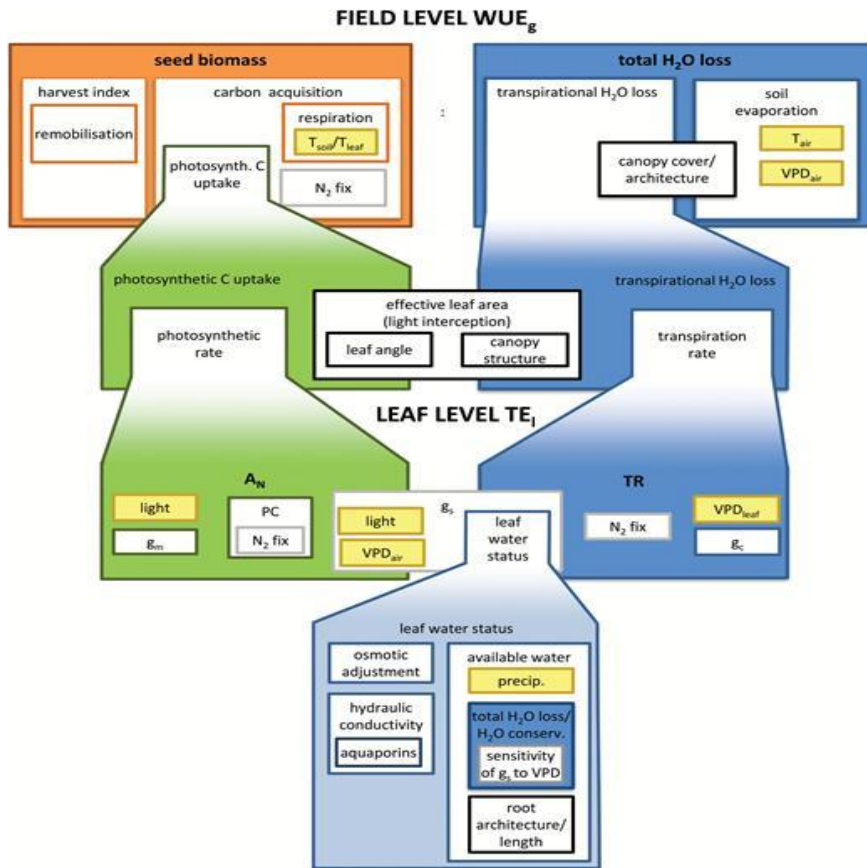

Figure 1 Dependencies of water use efficiency at field level (WUE$_g$) and transpiration efficiency at leaf level (TE$_{leaf}$) (Adopted from Blessing et al., 2018)

Image caption: Inner boxes influence outer boxes. Blue-coloured or framed boxes are related to water loss, while orange boxes are related to carbon allocation and green boxes to carbon uptake. Yellow boxes represent environmental drivers. Black boxes are related to plant morphology. Grey boxes indicate plant physiological traits that directly (gs) or indirectly (N$_2$ fix) influence both carbon and water status of the plant. VPDair, vapour pressure deficit in the air; VPDleaf, vapour pressure deficit based on leaf temperature; Tsoil, soil temperature; Tair, air temperature; Tleaf, leaf temperature; gs, stomatal conductance; gm, mesophyll conductance; gc, cuticular conductance; PC, photosynthetic capacity; N2 fix, biological nitrogen fixation (Adopted from Blessing et al., 2018)

Blessing et al. (2018) found that the water use efficiency at the field level (WUEg) and transpiration efficiency at the leaf level (TE$_{leaf}$) are influenced by a complex interplay of environmental drivers, plant morphology, and physiological traits. Key factors include carbon allocation, photosynthetic carbon uptake, and various forms of water loss, such as soil and canopy transpiration. Environmental drivers like air temperature, soil temperature, and vapor pressure deficit play significant roles in these processes. The study highlights the importance of stomatal conductance, leaf water status, and nitrogen fixation in regulating both carbon and water dynamics within plants. Overall, the integrated understanding of these factors is crucial for optimizing water use efficiency and improving crop resilience in varying environmental conditions.

5 Root Architecture and Nutrient Uptake Efficiency

5.1 Mechanisms of nutrient uptake in legumes

Legumes have evolved complex root systems that play a crucial role in nutrient uptake, particularly under stress conditions such as drought or nutrient deficiency. The root system architecture (RSA) of legumes, including traits like root length, root surface area, and root diameter, significantly influences their ability to acquire nutrients from the soil. For instance, a deep and proliferative root system can enhance water and nutrient uptake under drought conditions, as seen in grain legumes (Ye et al., 2018). Additionally, specific root traits such as root hair length and root branching are associated with improved nutrient foraging efficiency. In chickpea, genes related to phosphorus (P) acquisition and use efficiency have been identified, which can help in developing strategies to reduce P-fertilizer application (Thudi et al., 2021).

5.2 Correlation between root traits and nutrient acquisition

The correlation between root traits and nutrient acquisition is well-documented in various legume species. For example, in soybean, significant SNPs associated with root traits have been linked to improved nutrient uptake efficiency. Similarly, in lentil, root traits such as total root length, surface area, and root volume are correlated with drought tolerance and nutrient acquisition. In rapeseed, QTL mapping has revealed genomic regions controlling root architecture and shoot biomass under nitrogen, phosphorus, and potassium stress, indicating the critical role of these traits in nutrient uptake (Ahmad et al., 2022). Furthermore, specific root traits like root length and root:shoot ratio have been identified as promising for efficient phosphorus foraging in Fabales species (MacAlister et al., 2018).

5.3 Case studies on nutrient-efficient legume varieties

Several case studies highlight the development of nutrient-efficient legume varieties through genetic and genomic approaches. In chickpea, genome-wide association mapping has identified loci and genes associated with root traits that enhance phosphorus acquisition and use efficiency (Figure 2) (Thudi et al., 2021). In soybean, a genome-wide association study has identified genetic loci for RSA traits in field-grown conditions, providing insights into the genetic architecture of nutrient-efficient root systems (Dhanapal et al., 2021). Additionally, in pea, a comparative genome-wide association study has identified common loci controlling root architecture and resistance to root diseases, which can be combined with resistance QTL in breeding programs to develop nutrient-efficient varieties (Desgroux et al., 2018). These studies underscore the potential of integrating genetic and genomic tools to improve root traits and nutrient uptake efficiency in legumes.

Thudi et al. (2021) found that a specific SNP locus (Ca1_12310101) on chromosome Ca1 is significantly associated with three key traits in plants: physiological phosphorus-use efficiency, shoot dry weight, and shoot phosphorus content. These associations were identified using three different statistical models: GLM, MLM, and FarmCPU. The identification of significant marker-trait associations (MTAs) was achieved by applying Bonferroni correction to ensure statistical rigor. This finding highlights the potential of using genomic loci to predict and enhance desirable traits in plants, offering valuable insights for plant breeding and genetic improvement programs aimed at optimizing nutrient use efficiency and biomass production.

6 Breeding and Biotechnology Approaches

6.1 Conventional breeding for improved root traits

Conventional breeding has long been employed to enhance root traits in legumes, focusing on selecting superior genotypes through pedigree and performance-based selection. This method has been instrumental in improving legume genotypes, albeit with significant resource and time investments. Classical breeding methodologies have been extensively explored to address yield limitations in legumes, but the desired success rate has often been elusive (Afzal et al., 2019). Despite these challenges, conventional breeding remains a foundational approach, providing a basis for integrating more advanced genomic tools and technologies.
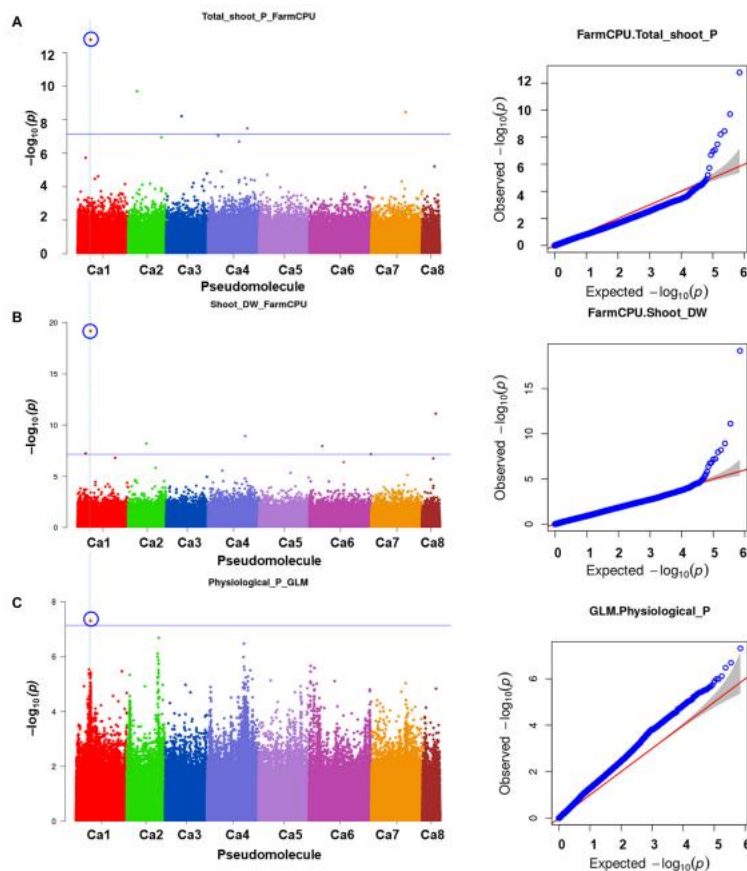
Figure 2 An SNP locus (Ca1_12310101) on Ca1 showing association with three traits (A) physiological phosphorus (P)-use efficiency, (B) shoot dry weight, and (C) shoot P content (Adopted from Thudi et al., 2021)

Image caption: Three different statistical models GLM, MLM, and FarmCPU were used to identify the MTAS. The significant MTAs were determined using Bonferroni correction (Adopted from Thudi et al., 2021)

6.2 Marker-assisted selection and genomic approaches
The advent of next-generation sequencing (NGS) and high-throughput genotyping platforms has revolutionized legume breeding. Marker-assisted selection (MAS) and genomic selection (GS) have been pivotal in developing superior lines with enhanced root traits. These approaches involve the use of high-density genetic maps, quantitative trait loci (QTLs) identification, and single nucleotide polymorphisms (SNPs) to accelerate genetic gains (Varshney et al., 2018). For instance, the development of HapMaps and re-sequencing of several hundred lines have facilitated the identification of markers associated with key agronomic traits, including root architecture (Varshney et al., 2018). The integration of genomics, phenotyping, and systems modeling is proposed to further enhance genetic gains, particularly under drought conditions (Ye et al., 2018). This holistic approach aims to improve root system architecture (RSA) for better water and nutrient uptake efficiency.

6.3 Genetic engineering and Crispr/Cas9 applications
Genetic engineering, particularly CRISPR/Cas9 gene editing, offers transformative potential for legume crop improvement. This technology allows for precise modifications of target genes associated with root traits, thereby accelerating the development of cultivars with enhanced nutrient uptake and stress resilience. CRISPR/Cas9 has been successfully applied to several legume species, including soybean, cowpea, and chickpea, although challenges remain in terms of in vitro gene transfer and regeneration for some legumes. The regulatory environment and public acceptance are critical factors that will influence the widespread adoption of CRISPR technology in legume breeding (Figure 3) (Bhowmik et al., 2021). Despite these challenges, the potential benefits of CRISPR/Cas9 in improving root architecture and overall crop performance are substantial.
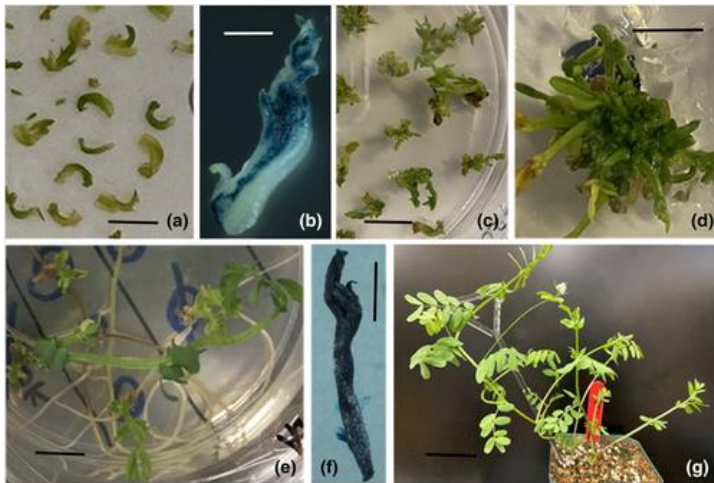
Figure 3 Example of transformation and regeneration stages, as shown for lentil (Adopted from Bhowmik et al., 2021)

Image caption: (a) Slices of embryo axes after 4 days of co-cultivation with Agrobacterium, (b) transient gus expression in an explant at the end of co-cultivation, (c) explants at the end of a shoot induction phase, (d) explants during the shoot elongation phase, (e) rooted shoots, (f) gus expression in small shoot at the end of shoot elongation after staining with X-glucuronidase, and (g) a rooted putative transformant in soil. Scale bars: (a) 5 mm, (b) 1 mm, (c) 5 mm, (d) 3 mm, (e) 5 mm, (f) 5 mm, and (g) 4 cm (Adopted from Bhowmik et al., 2021)

Bhowmik et al. (2021) found that the transformation and regeneration process in lentil plants involves several distinct stages, beginning with the co-cultivation of embryo axis slices with Agrobacterium. This is followed by transient expression of the gus gene, which serves as a marker for successful transformation. The subsequent stages include shoot induction and elongation phases, where the explants develop into shoots. Rooted shoots are then observed, and the presence of the gus gene in these shoots confirms successful genetic transformation. Finally, the transformed shoots are transferred to soil, resulting in the establishment of rooted putative transformants. This comprehensive approach ensures the effective introduction and stable integration of desired genetic traits in lentil plants, providing a valuable methodology for genetic engineering and crop improvement.

7 Implications for Sustainable Agriculture

7.1 Enhancing crop productivity and resilience

The genetic improvement of root system architecture (RSA) in legumes has significant implications for enhancing crop productivity and resilience, particularly under stress conditions such as drought. A deep and proliferative root system can improve water and nutrient uptake, which is crucial for maintaining crop yields in water-limited environments (Ye et al., 2018). Advances in genomics and phenotyping techniques have facilitated the identification of beneficial root traits, enabling the development of legume varieties with enhanced drought tolerance and yield potential (Kumar et al., 2020). Additionally, the integration of modern genomics approaches and simulation modeling can accelerate genetic gains, leading to the development of more resilient legume varieties that can thrive under adverse conditions (Varshney et al., 2018).

7.2 Reducing dependency on chemical fertilizers

Intercropping legumes with cereals has been shown to increase nutrient use efficiency, particularly phosphorus and nitrogen, thereby reducing the need for chemical fertilizers. Studies have demonstrated that intercropping can enhance phosphorus use efficiency and reduce phosphorus fertilizer requirements by 21% compared to sole cropping. Similarly, intercropping grain legumes with cereals can improve nitrogen use efficiency, reducing the requirement for synthetic nitrogen fertilizers by approximately 26% on a global scale. The symbiotic relationships between legumes and nitrogen-fixing bacteria, as well as the beneficial interactions with plant growth-promoting rhizobacteria (PGPR), further contribute to reducing the dependency on chemical fertilizers (Swarnalakshmi et al., 2020).

7.3 Potential impact on soil health and ecosystem services

Improving root architecture in legumes not only enhances nutrient uptake but also positively impacts soil health and ecosystem services. Root traits such as root length, root hairs, and root branching can influence the structure and function of microbial communities in the rhizosphere, promoting beneficial microbial interactions that enhance nutrient cycling and soil fertility (Galindo-Castañeda et al., 2022). The use of legumes in intercropping systems can also improve soil nitrogen acquisition and reduce the need for synthetic fertilizers, thereby minimizing the environmental impact of agricultural practices (Jensen et al., 2020). Additionally, legumes contribute to soil health through biological nitrogen fixation, which replenishes soil nitrogen levels and supports sustainable agricultural practices (Yang et al., 2022).

In summary, the genetic improvement of root architecture in legumes holds great promise for enhancing crop productivity and resilience, reducing dependency on chemical fertilizers, and improving soil health and ecosystem services. These advancements are crucial for developing sustainable agricultural systems that can meet the growing global food demand while minimizing environmental impacts.

8 Future Directions and Research Gaps

8.1 Unresolved questions and challenges

Despite significant advancements in understanding the genetics of root architecture in legumes, several unresolved questions and challenges remain. One major challenge is the complexity of root traits and their interactions with environmental factors, which complicates the identification of key genetic components. For instance, while numerous quantitative trait loci (QTLs) associated with root system architecture (RSA) have been identified, the functional validation of these loci remains limited (Ye et al., 2018). Additionally, the genetic basis of root traits under varying nutrient conditions, such as phosphorus and nitrogen availability, is not fully understood (Thudi et al., 2021). Another challenge is the integration of root traits with other agronomic traits, such as disease resistance and yield, to develop holistic breeding strategies (Desgroux et al., 2018).

8.2 Emerging technologies and methodologies

Emerging technologies and methodologies offer promising avenues to address these challenges. High-throughput phenotyping platforms, including image-based approaches and non-invasive methods like X-ray CT and MRI, are revolutionizing the study of RSA by enabling detailed and large-scale phenotyping. Genotyping-by-sequencing (GBS) and genome-wide association studies (GWAS) are powerful tools for identifying genetic loci associated with root traits and nutrient use efficiency (Katuuramu et al., 2018). Additionally, advances in computer vision and spatiotemporal root simulation modeling are enhancing our understanding of root physiology and ecology. The integration of pan-genome resources and in-field phenotyping platforms holds potential for precise selection of superior genotypes with improved RSA (Reddy et al., 2020).

8.3 Integrative approaches for holistic understanding

To achieve a holistic understanding of root architecture and its implications for nutrient uptake efficiency, integrative approaches that combine genomics, phenomics, and systems modeling are essential. The integration of modern genomics approaches with high-throughput phenotyping and simulation modeling can accelerate genetic gains in legumes. Furthermore, understanding the tripartite interactions between legumes, arbuscular mycorrhizal fungi, and rhizobia can provide insights into the synergistic effects on nutrient uptake and carbon allocation. Combining genetic resistance with architectural traits that limit disease development is another promising strategy for improving legume resilience and yield (Varshney et al., 2018). Overall, a multidisciplinary approach that incorporates genetic, physiological, and ecological perspectives is crucial for advancing our knowledge of root architecture in legumes and its role in nutrient uptake efficiency.

9 Concluding Remarks

The genetics of root architecture in legumes play a crucial role in enhancing nutrient uptake efficiency, particularly under stress conditions such as drought and nutrient limitations. Several studies have highlighted the

importance of root system architecture (RSA) traits, including root length, root hairs, root branching, root diameter, and root proliferation rate, in improving water and nutrient uptake efficiency. The identification of quantitative trait loci (QTLs) and candidate genes associated with beneficial root traits has been a significant advancement in this field. For instance, genes like *PSTOL1*, *qSOR1*, and *DRO1* have been identified as key players in enhancing root growth and nutrient uptake under various stress conditions. Additionally, the integration of high-throughput phenotyping techniques and omics approaches has facilitated the dissection of the genetic basis of RSA traits, enabling the development of more resilient legume cultivars.

The findings from these studies have several implications for future research and agricultural practices. Firstly, there is a need for further exploration of the genetic diversity in legume germplasm to identify novel RSA traits and associated genes that can be utilized in breeding programs. The use of advanced phenotyping platforms and machine learning techniques can enhance the precision and efficiency of selecting desirable root traits. Moreover, understanding the interactions between root architecture and root-associated microorganisms can provide new opportunities to improve nutrient and water uptake through synergistic effects. In agricultural practices, the development of legume varieties with optimized root systems can lead to better resource use efficiency and higher yields, particularly in environments with limited water and nutrient availability. Breeding programs should focus on selecting root phenotypes that are well-adapted to specific edaphic conditions and stress environments. Additionally, integrating knowledge of root traits with soil management practices and microbial inoculants can further enhance the sustainability and productivity of legume crops. Overall, the continued research and application of genetic insights into root architecture hold great promise for improving legume crop performance and contributing to global food security.

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Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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