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General characteristics of the factors influencing the effectiveness of symbiotic relationships between legumes and bacteria

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ABSTRACT

Legumes form nitrogen-fixing partnerships with rhizobial bacteria that support plant nutrition, soil fertility, and more sustainable crop production. Yet the benefits of this association vary widely across soils, climates, and host–microbe combinations. This narrative review examines the biological and environmental factors governing symbiotic effectiveness, with particular attention to soil acidity, temperature, salinity, drought, waterlogging, light, and mineral nutrients. Drawing on published research, it explains how these factors influence rhizobial survival, molecular recognition, nodule formation, photosynthetic carbon supply, and nitrogenase activity. The synthesis also considers host–rhizobial specificity, plant regulation of symbiotic investment, and the combined effects of environmental stresses. Evidence indicates that suitable environmental conditions alone cannot ensure effective nitrogen fixation: compatible partners, balanced nutrition, and functional nodules are equally important. The agricultural implications are discussed with reference to Azerbaijan, particularly the salinity-affected Kur-Araz Lowland, where local field evidence on legume nitrogen fixation remains limited. Integrated management, including appropriate soil amendments, water management, and locally adapted inoculants, may improve symbiotic performance, but recommendations require crop- and site-specific validation. Future research should prioritize combined-stress experiments, direct measures of nitrogen fixation, and multi-season field trials. A better understanding of these interacting controls could help translate legume–rhizobia symbiosis into reliable gains in productivity, fertilizer efficiency, and agricultural resilience.

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INTRODUCTION

Biological nitrogen fixation (BNF) is one of the most important natural processes supporting soil fertility, plant productivity, and sustainable agricultural development. Nitrogen is an essential nutrient required for plant growth and development, particularly for the synthesis of proteins, nucleic acids, chlorophyll, and other biologically important compounds. Although atmospheric nitrogen is abundant, most plants cannot utilize it directly. Instead, they depend on nitrogen available in the soil or converted into biologically accessible forms through microbial activity. Among the various nitrogen-fixing mechanisms, the symbiotic relationship between leguminous plants and rhizobial bacteria represents an efficient and environmentally beneficial process that contributes significantly to agricultural productivity and ecosystem sustainability (Kebede, 2021).

Leguminous plants have developed a remarkable biological association with soil microorganisms, particularly nitrogen-fixing bacteria commonly known as rhizobia. Through this mutually beneficial relationship, rhizobia colonize plant roots and stimulate the formation of specialized structures called root nodules, where atmospheric nitrogen is converted into ammonia through the activity of the nitrogenase enzyme. In return, the host plants provide carbohydrates and other organic compounds derived from photosynthesis to support bacterial growth and metabolic activities. The establishment of this symbiotic relationship involves several coordinated biological processes, including molecular recognition between the host plant and bacteria, infection thread formation, bacterial entry into root tissues, and nodule development (Kitaeva *et al.*, 2016). The successful coordination of these processes is essential for effective nitrogen fixation and improved plant performance.

The agricultural importance of legume–rhizobia symbiosis extends beyond the direct supply of nitrogen to host plants. Biological nitrogen fixation can reduce the need for synthetic nitrogen fertilizers, improve soil nutrient availability, and support environmentally responsible crop production. Excessive application of chemical nitrogen fertilizers is associated with several environmental concerns, including nutrient leaching, water pollution, greenhouse gas emissions, and soil degradation. Consequently, strengthening biological nitrogen fixation has become an important strategy for developing sustainable agricultural systems, particularly in regions where fertilizer costs, declining soil fertility, and environmental pressures limit agricultural productivity (Kebede, 2021). The integration of legumes into crop rotation and diversified farming systems may also improve nutrient cycling and contribute to long-term soil health.

Despite its ecological and agricultural benefits, the efficiency of biological nitrogen fixation is not constant under different environmental conditions. The establishment, development, and functioning of legume–rhizobia symbiosis are influenced by several abiotic factors, including soil acidity, temperature, moisture availability, salinity, light intensity, and mineral nutrient concentrations. These environmental conditions can directly affect the survival and activity of rhizobial populations while also influencing plant growth, root development, photosynthetic activity, and nodule formation. Their effects may occur independently or interact with one another, making the regulation of biological nitrogen fixation a complex physiological and ecological process (Goyal and Habtewold, 2023; Nzeyimana *et al.*, 2024).

Soil pH is among the major factors determining the successful establishment of symbiotic relationships. Acidic conditions may inhibit rhizobial survival, bacterial attachment to root hairs, infection thread development, and root nodule formation. Such conditions can also interfere with the molecular signaling processes required for successful plant–microbe interactions. Although different legume species and rhizobial strains demonstrate varying levels of tolerance to soil acidity, conditions

approaching neutral pH are generally more favorable for effective symbiotic activity (Ferguson *et al.*, 2013; Hawkins and Oresnik, 2022; Goyal and Habtewold, 2023).

Temperature and water availability are equally important in regulating symbiotic nitrogen fixation. Both high and low temperatures can affect microbial metabolism, plant physiological processes, and the development and functioning of root nodules. These challenges are becoming increasingly relevant under changing climatic conditions, particularly where rising temperatures and irregular rainfall patterns influence agricultural ecosystems (Rubenstein *et al.*, 2023). Similarly, drought stress reduces photosynthetic activity, limits nutrient transport, disrupts plant metabolism, and negatively affects rhizobial colonization and nitrogen fixation. Excessive soil moisture may also create unfavorable conditions for nodule functioning, demonstrating the importance of maintaining suitable soil water conditions for effective symbiosis (Chammakhi *et al.*, 2022).

Soil salinity represents another major environmental constraint affecting leguminous crops and their associated microorganisms. Increased salt concentrations can impair plant growth, alter microbial community composition, reduce bacterial viability, and interfere with nodule development and physiological activity. These effects ultimately reduce nitrogen fixation efficiency and crop productivity (Gamalero *et al.*, 2020). In addition, light availability and mineral nutrition influence the symbiotic system through their effects on photosynthesis, carbon allocation, and nodule metabolism. Phosphorus is particularly important for energy-dependent nitrogen fixation, while calcium, magnesium, potassium, and other essential nutrients contribute to symbiotic signaling, metabolic regulation, and normal nodule functioning. Conversely, excessive mineral nitrogen availability may suppress nodulation and reduce the plant's dependence on symbiotic nitrogen fixation (Liu *et al.*, 2018; Ma *et al.*, 2025; Li *et al.*, 2024).

These environmental challenges are particularly relevant to agricultural regions characterized by diverse climatic conditions, soil degradation, water limitations, and salinization. Azerbaijan provides an important regional context because its agricultural landscapes include areas affected by soil salinity and variable moisture conditions. More than 600,000 hectares of land in Azerbaijan have been reported to experience salinity-related problems, with particular concerns in the Kura-Araz Lowland, an important agricultural region (Aliyev *et al.*, 2023). Understanding how abiotic stresses influence legume–rhizobia interactions under such conditions could support the development of more effective crop management strategies and improve the utilization of biological nitrogen fixation in regional agriculture.

Although numerous studies have examined individual environmental factors affecting legume–rhizobia symbiosis, understanding their combined influence remains essential for improving the practical application of biological nitrogen fixation. Differences in plant species, rhizobial strains, soil properties, and climatic conditions may lead to considerable variation in symbiotic performance. Therefore, identifying stress-tolerant legume varieties and effective rhizobial strains, together with appropriate soil and nutrient management practices, represents an important direction for future agricultural research.

The objective of this review is to examine and synthesize existing scientific evidence on the effects of major abiotic environmental factors, particularly soil pH, temperature, salinity, moisture, light, and mineral nutrient availability, on legume–rhizobia symbiosis and biological nitrogen fixation. The review also considers the implications of these environmental factors for sustainable agricultural development, with particular attention to the agricultural conditions of Azerbaijan. By highlighting the environmental constraints and potential management approaches associated with biological nitrogen fixation, this review aims to contribute to a better understanding of plant–microbe interactions and their potential application in improving soil fertility, agricultural productivity, food security, and environmental sustainability.

RESULTS AND DISCUSSION

The available evidence indicates that successful symbiotic nitrogen fixation depends not only on the genetic compatibility of leguminous plants and their associated rhizobia but also on the environmental conditions under which the relationship develops. Abiotic stresses can interfere with different stages of symbiosis, from early molecular signaling and infection thread formation to mature nodule functioning and nitrogen fixation. Understanding these interactions is therefore essential for improving legume productivity, reducing dependence on synthetic fertilizers, and strengthening the resilience of agricultural systems.

Influence of soil pH on legume–rhizobia symbiosis

Soil pH is a fundamental environmental factor affecting the survival, growth, and symbiotic performance of rhizobial bacteria. The reviewed literature indicates that most agricultural legumes establish more effective symbiotic relationships under slightly acidic to neutral soil conditions, although the optimum pH varies according to the legume species, rhizobial strain, and soil characteristics. Strongly acidic soils generally restrict biological nitrogen fixation by affecting both the host plant and its microbial partner.

Under acidic conditions, increased concentrations of hydrogen ions and potentially toxic elements, particularly aluminum and manganese, can impair root development and nutrient uptake. These changes may also reduce rhizobial survival and interfere with the molecular communication required for successful symbiosis. Plant-derived flavonoids normally stimulate the expression of bacterial nodulation genes, initiating the signaling pathways involved in root hair infection and nodule development. Soil acidity can disrupt these processes, resulting in reduced bacterial attachment, impaired infection thread formation, and delayed nodule initiation.

Ferguson *et al.* (2013) demonstrated that acidic growth conditions affect several stages of legume nodulation, including bacterial colonization and early nodule development. Their review also highlighted differences in acid tolerance among legume species and rhizobial strains. More recent evidence synthesized by Yeremko *et al.* (2025) further confirms that soil acidity can substantially reduce rhizobial activity, nodule formation, and nitrogen fixation efficiency.

The effects of soil acidity become particularly important when soil pH falls below approximately 5.5, although this threshold should not be considered universal. Some rhizobial strains can tolerate relatively acidic conditions, while others require a narrower pH range for effective growth and nodulation. This variation suggests that improving symbiotic performance requires consideration of both partners rather than soil pH alone.

From an agricultural perspective, appropriate soil amendments, particularly liming where justified by soil testing, may help improve conditions for rhizobial activity. The selection of acid-tolerant legume cultivars and compatible bacterial strains provides another promising strategy.

Overall, the reviewed evidence suggests that soil pH influences biological nitrogen fixation through interconnected effects on microbial survival, root physiology, nutrient availability, and symbiotic signaling. Effective soil acidity management should therefore be regarded as an important component of sustainable legume production.

Effects of temperature on symbiotic nitrogen fixation

Temperature plays a central role in regulating the physiological and biochemical activities of both leguminous plants and rhizobial bacteria. The development of an effective symbiotic relationship requires suitable temperature conditions for bacterial growth, root infection, nodule formation, and nitrogenase activity.

Published literature describes approximately 28–31°C as a favorable temperature range for certain root-associated bacterial activities. However, the optimum temperature for biological nitrogen fixation varies considerably among legume species, rhizobial strains,

and environmental conditions. Consequently, this range should be interpreted as an example rather than a universal optimum.

High temperatures may reduce rhizobial viability, disturb plant–microbe signaling, inhibit root nodule development, and accelerate nodule deterioration. Heat stress can also affect photosynthesis and carbon metabolism, limiting the energy available to support nitrogen fixation. Conversely, low temperatures may slow bacterial multiplication, delay root infection, and reduce the metabolic activity of developing nodules.

Research reviewed by Yeremko *et al.* (2025) demonstrates that temperature affects both rhizobial communities and the establishment of effective symbiosis. Temperature responses depend strongly on the physiological characteristics and adaptation of the interacting organisms.

These observations are particularly relevant in the context of climate change. Increasing temperature variability and more frequent heat extremes may create unfavorable conditions for symbiotic nitrogen fixation, especially in regions already experiencing water shortages or soil degradation.

Nevertheless, some legume species and rhizobial strains possess physiological adaptations that enable them to function under comparatively high temperatures. Identifying these stress-tolerant combinations could improve biological nitrogen fixation in warmer agricultural environments.

The evidence suggests that future research should focus on determining temperature tolerance at different stages of symbiosis, evaluating locally adapted rhizobial populations, and developing legume–rhizobia combinations capable of maintaining effective nitrogen fixation under changing climatic conditions.

Influence of soil salinity on rhizobial activity and nodule development

Soil salinity is a major constraint to agricultural productivity in arid and semi-arid regions; particularly where irrigation practices, high evaporation rates, and insufficient drainage contribute to salt accumulation. Salinity affects legume–rhizobia symbiosis through several interconnected physiological and microbiological mechanisms.

Elevated salt concentrations reduce the ability of plants to absorb water and may cause ionic imbalances, nutrient deficiencies, and oxidative stress. These changes impair root growth and photosynthetic activity, thereby limiting the availability of carbohydrates needed to sustain symbiotic nitrogen fixation.

Rhizobial bacteria are also sensitive to saline conditions. Salt stress can reduce bacterial survival, alter rhizosphere microbial communities, and interfere with the early stages of root colonization. In established symbioses, salinity may impair nodule respiration, reduce leghaemoglobin content, and limit nitrogenase activity.

Research drawing on Gamalero *et al.* (2020), emphasizes the negative influence of salinity on infection thread development and nodule functioning. Recent research has additionally highlighted that the legume–rhizobia relationship may itself contribute to plant stress tolerance through physiological and biochemical adjustments. Wang *et al.* (2026) describe symbiotic nodulation as a potentially important mechanism for improving legume performance under abiotic stress.

This relationship suggests that the effects of salinity are not entirely one-directional. Although salt stress can weaken symbiotic nitrogen fixation, effective associations with tolerant rhizobia may help plants maintain growth and nutrient acquisition under moderately stressful conditions. The extent of this benefit depends on the host genotype, bacterial strain, salt concentration, and duration of exposure.

For agricultural management, selecting salt-tolerant legumes and rhizobial strains, improving drainage, and adopting suitable irrigation practices may help reduce the negative effects of salinity. However, microbial

inoculation should be regarded as a complementary approach rather than a substitute for effective soil and water management.

The findings indicate that salinity management is particularly important for sustaining legume production in regions where salt accumulation threatens soil fertility and crop productivity.

Effects of soil moisture, drought, and waterlogging

Water availability is essential for the growth and physiological functioning of both plants and microorganisms. In legume–rhizobia symbiosis, soil moisture influences root development, microbial mobility, nutrient transport, nodule metabolism, and nitrogen fixation.

Drought stress reduces plant water potential and interferes with several physiological processes, including photosynthesis, stomatal regulation, nutrient uptake, and carbohydrate transport. These disturbances can reduce the supply of energy and organic compounds required to maintain active root nodules.

Water deficiency may also reduce rhizobial survival and restrict the development of infection threads and new nodules. In established nodules, drought can impair respiration and nitrogenase activity, resulting in reduced nitrogen fixation and plant nitrogen availability.

Published literature describes reduced photosynthetic activity, changes in plant hormonal balance, and restricted root and shoot growth as important consequences of water stress. These observations are consistent with the broader scientific literature describing drought as a major limitation to symbiotic nitrogen fixation.

Excessive soil moisture can also negatively affect nodulation and nitrogen fixation. Waterlogged soils have limited oxygen diffusion, which may disrupt root respiration and the controlled oxygen supply required for normal nodule metabolism. Although nitrogenase is sensitive to oxygen, active nodules still require adequate oxygen for energy production. Consequently, both insufficient and excessive soil moisture can interfere with symbiotic functioning.

Yeremko *et al.* (2025) discuss the influence of drought and waterlogging on the metabolic and hormonal regulation of legume–rhizobia interactions. Their review supports the importance of maintaining suitable soil moisture conditions rather than simply increasing water availability.

The development of drought-tolerant legume cultivars and compatible rhizobial strains represents a promising approach for improving nitrogen fixation in water-limited environments. Water-conserving agricultural practices, including mulching, improved soil organic matter management, and appropriate irrigation scheduling, may also support more stable symbiotic performance.

These findings demonstrate that soil moisture management is an essential consideration for sustaining biological nitrogen fixation, particularly under increasingly variable rainfall conditions.

Role of light and photosynthetic activity in symbiotic nitrogen fixation

Light is an essential environmental factor influencing biological nitrogen fixation because it regulates photosynthesis and the production of organic compounds required for plant growth and microbial metabolism. Although rhizobia perform nitrogen fixation within root nodules, the energy needed to sustain this process is largely derived from carbon compounds supplied by the host plant.

During photosynthesis, plants convert solar energy into chemical energy and synthesize carbohydrates that are subsequently transported to different plant organs, including roots and nodules. Within the symbiotic system, these compounds provide the carbon substrates needed for bacterial respiration and ATP production, which are essential for nitrogenase activity.

Reduced light availability may limit photosynthetic carbon assimilation, decrease carbohydrate transport to nodules, and ultimately restrict nitrogen fixation. Prolonged shading can therefore influence symbiotic efficiency, although the magnitude of its effect depends on plant species, developmental stage, and other environmental conditions.

Previous research also emphasizes the importance of root exudates, including sugars, organic acids, and secondary metabolites, in supporting rhizosphere microbial communities. These substances contribute to the establishment and maintenance of beneficial plant–microorganism interactions.

Light availability should therefore be considered alongside water and nutrient availability when evaluating symbiotic performance. For example, drought stress may reduce photosynthesis even when sunlight is sufficient, whereas nutrient deficiencies can limit the plant's ability to convert available light into productive growth.

The reviewed evidence indicates that effective biological nitrogen fixation depends on a continuous supply of photosynthetically derived carbon. Consequently, agricultural practices that promote healthy canopy development, balanced plant nutrition, and adequate water availability may indirectly support more effective nitrogen fixation.

Influence of mineral nutrients on legume–rhizobia symbiosis

Mineral nutrient availability is another important factor determining the establishment and efficiency of legume–rhizobia symbiosis. Although biological nitrogen fixation provides legumes with an alternative nitrogen source, the process itself requires adequate supplies of several essential macro- and micronutrients.

Nitrogen availability

Nitrogen is essential for plant growth, but excessive mineral nitrogen in the soil can suppress the establishment and functioning of nitrogen-fixing nodules. When nitrate or ammonium is readily available, legumes may preferentially absorb these forms of nitrogen rather than invest energy in symbiotic nitrogen fixation.

This response is associated with regulatory mechanisms that control nodule formation and nitrogenase activity. Ferguson *et al.* (2013) described how external nitrogen compounds can activate plant signaling pathways that restrict nodulation. More recent literature also confirms that high mineral nitrogen availability may reduce root infection, nodule development, and symbiotic activity.

However, the relationship between soil nitrogen availability and biological nitrogen fixation is not entirely negative. Limited mineral nitrogen may support early plant establishment before nodules become fully functional, particularly in soils with low fertility. The appropriate nitrogen management strategy therefore depends on the crop, soil nitrogen supply, and stage of plant development.

These findings suggest that excessive nitrogen fertilization should be avoided where effective biological nitrogen fixation can meet a substantial proportion of crop nitrogen requirements.

Phosphorus availability

Phosphorus plays a particularly important role in symbiotic nitrogen fixation because nitrogenase activity requires considerable energy in the form of ATP. Adequate phosphorus availability supports root development, nodule formation, energy metabolism, and the maintenance of active nitrogen-fixing tissues.

Phosphorus deficiency can reduce nodule number and size, impair nitrogenase activity, and limit nitrogen fixation. The supplied manuscript also identifies reduced leghaemoglobin content and changes in nodule metabolism as important consequences of inadequate phosphorus supply.

Recent research on nutrient-dependent regulation of symbiotic nitrogen fixation confirms that phosphorus availability is closely associated with root and nodule development. Appropriate phosphorus management can therefore improve symbiotic performance in deficient soils, although the response depends on soil properties and crop requirements.

Potassium, calcium, magnesium, and other essential nutrients

In addition to nitrogen and phosphorus, several other mineral elements contribute to the development and functioning of legume–rhizobia symbiosis.

Potassium supports plant water regulation, enzyme activity, and physiological responses to environmental stress. Calcium is involved in cellular signaling and the molecular recognition processes required for successful root infection and nodule initiation. Magnesium contributes to photosynthesis, energy metabolism, and the transport and utilization of carbon and nitrogen compounds within plant tissues.

Micronutrients also have important functions. Iron is required for nitrogenase-associated proteins and leghaemoglobin, while molybdenum is an essential component of the conventional molybdenum-dependent nitrogenase enzyme complex. Deficiencies in these elements can restrict nitrogen fixation even when other environmental conditions are favorable. Yeremko *et al.* (2025) provide a detailed discussion of these nutrient relationships, emphasizing the importance of balanced mineral nutrition for maintaining effective symbiosis.

Overall, mineral nutrient management should aim to maintain adequate nutrient availability without unnecessarily suppressing the biological processes that make legumes valuable in sustainable agriculture.

Host–rhizobial compatibility and biological regulation

Environmental suitability alone does not guarantee successful nitrogen fixation. Legume species differ in their ability to recognize particular rhizobial partners, and even strains capable of producing nodules may differ greatly in the nitrogen they supply. Molecular recognition, bacterial signaling, plant immune responses, and subsequent nodule development determine whether a partnership becomes productive. Yu and Zhu (2025) describe substantial variation in symbiotic specificity among host–microbe combinations. Thus, inoculant selection should consider both local environmental adaptation and compatibility with the intended crop.

The plant also regulates the costs and benefits of its microbial partnership. Porter *et al.* (2024) explain that host control mechanisms can favor beneficial rhizobia and limit investment in poorly performing strains. This provides an important distinction between nodule number and functional nitrogen fixation: abundant nodules are not necessarily evidence of effective nitrogen supply. Field evaluations should combine nodulation measurements with plant nitrogen status, biomass, yield, and, where feasible, direct estimates of nitrogen fixation.

Interactions among abiotic stressors and management trade-offs

Under field conditions, temperature, water availability, soil chemistry, and nutrient status interact rather than operate independently. Drought may intensify salt stress by concentrating dissolved salts, while high temperatures can increase evapotranspiration and reduce photosynthetic carbon supply. Soil acidity can simultaneously constrain rhizobial survival and phosphorus availability. These overlapping constraints help explain why a strain that performs well under controlled conditions may fail to deliver equivalent benefits on farms.

Management should therefore be site-specific. Liming may be useful in acidic soils but inappropriate without soil testing; inoculation is more likely to succeed when a compatible and competitive strain is available; phosphorus correction may support nodulation in deficient soils but cannot compensate for severe waterlogging or

salinity. The nutrient-regulation synthesis of Ma *et al.* (2025) further shows that external nitrogen supply, phosphate transport, and calcium signaling jointly influence nodule establishment and function. Integrated interventions should be evaluated for their effects on both fixation and crop yield.

Relevance to azerbaijan and evidence limitations

Azerbaijan offers an important applied setting, particularly in the Kur-Araz Lowland, where irrigation, drainage, climate, and soil salinity affect crop production. Han *et al.* (2024) reconstructed changes in regional salinity using satellite data and modeling, finding that rainfall and drainage improvements had reduced salinity during the study period while future re-salinization remained a concern. This study supports the regional importance of salinity management, but it did not measure rhizobial nodulation or biological nitrogen fixation directly. Claims about the magnitude of symbiotic losses in Azerbaijan therefore require dedicated crop- and site-specific evidence.

A useful research program would pair soil salinity and moisture monitoring with rhizobial isolation, host compatibility screening, nodule activity measurements, and replicated field trials. Comparisons should include locally adapted cultivars and strains, uninoculated controls, and agronomically relevant management treatments. Multi-season trials would help distinguish short-term responses from stable benefits across changing environmental conditions.

Research priorities and overall interpretation

Future work should move beyond single-factor stress experiments toward factorial tests of salinity, temperature, moisture, and nutrient availability. Researchers should report host genotype, strain identity, soil characteristics, stress duration, and measurements of functional nitrogen fixation. Genomic and physiological investigations can clarify stress-tolerance mechanisms, but they should be linked to field performance. Economic and environmental assessments are also needed to determine when biological inputs genuinely reduce fertilizer demand without compromising yields.

Taken together, the literature suggests that effective symbiosis emerges from the interaction of compatible biological partners with suitable environmental and nutritional conditions. No single pH, temperature, or nutrient recommendation applies to every crop–rhizobium combination. Sustainable application depends on identifying the dominant local constraints and testing integrated solutions against meaningful agronomic outcomes.

CONCLUSION

Legume–rhizobia symbiosis can improve nitrogen availability and reduce reliance on synthetic fertilizers, but its agricultural value depends on both host–microbe compatibility and the conditions in which the partners interact. The reviewed evidence shows that acidity, temperature extremes, salinity, drought, waterlogging, insufficient light, and nutrient imbalance can disrupt bacterial survival, nodulation, carbon supply, and nitrogenase activity. These stresses frequently occur together, making integrated management more relevant than single-factor interventions. Selecting compatible, stress-tolerant legume–rhizobia combinations, maintaining balanced soil fertility, and improving water and salinity management may help sustain nitrogen fixation. For Azerbaijan, especially the Kur-Araz Lowland, locally grounded field studies are needed to test these approaches and quantify their effects on nodulation, functional nitrogen fixation, yields, and fertilizer demand. Further research should prioritize combined-stress experiments and long-term field validation before broad agronomic recommendations are made.

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