TARLA BİTKİLERİ YETİŞTİRME VE ISLAHI DEĞERLENDİRMELERİ

Editör: Prof.Dr. Mehmet ÖZ

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Tarla Bitkileri Yetiştirme ve Islahı Değerlendirmeleri

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İÇİNDEKİLER

TARIMDA YEŞİL BİYOTEKNOLOJİ VE CRISPR-AL KULLANIMININ İNCELENMESİ

Birol TAŞ[1]

1. GİRİŞ

Günümüzde gıda güvenliği ve sürdürülebilir tarım dünya çapında önemli bir sorun haline gelmiştir. Bitkisel ve hayvansal üretim gibi tarımsal üretkenliğin temel faktörlerinin verimliliği, küresel iklim değişikliği ve küresel nüfusun beklenmedik şekilde artması nedeniyle tehlike altına girmiştir (Shongwe ve ark., 2014). İklim değişikliğinin tarımsal üretim ve gıda güvenliği üzerindeki bu sorunlara, eğer yakın gelecekte uygun bir çözüm bulunamazsa, çok yakın zamanda ciddi bir sorun olarak önümüze çıkacaktır. Çünkü, yaşanan iklim değişikliği ve olumsuz hava olayları, tarımsal üretimi azaltacak, azalan verimi arttırmak isteyen üretici tarlaya daha fazla gübre atacak, sonuç olarak kimyasal gübre kullanımının artmasıyla topraklar tuzlulaşacak ve toprak kirliliği artacaktır (Godfray ve Garnett, 2014) Sonuç olarak azalan üretim nedeniyle yetersiz beslenme veya açlık sorunu ortaya çıkacaktır (Kumsa ve Joner, 2010). Önceki çalışmalar, Sahra Altı Afrika'nın 2050 yılına kadar, buğday veriminin %22 (Goldenberg, 2014), pirinç veriminin %14 pirinç ve mısır veriminin %5'lik bir düşüş yaşanacağını belirtmiştir (Fernandez, 2011). Bu durum, iklim değişikliğinin gıda güvenliğine yönelik tehdidin boyutunu da göstermektedir.

Açıkça görülüyor ki, tarım teknolojisinin mevcut durumu, önümüzdeki üretim zorluklarını karşılamaya

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yetmeyecektir. Gelecekte yeterli gıda mevcudiyeti/verim artışı sağlamak için ek tarım arazisi veya stres direnci özellikleri yüksek yeni bitki çeşitleri elde etmek için yenilikçi biyoteknolojik araçların benimsenmesi zorunlu hale gelmiştir (Edgerton, 2009). Küresel tüketiciler için yeşil biyoteknoloji ile elde edilmiş ürünlerden elde edilen gıda mevcudiyeti, birincil gıda üretim sistemlerimizin verimliliğini ve etkinliğini artırarak, gıda işleme sırasında israfı azaltarak, gıda tedarikine erişimi iyileştirerek ve özellikle gelişmekte olan ülkelerde tüketiciler için gıda maliyetlerini düşürerek iyileştirilebilir. Biyoteknoloji kendi başına dünyanın gıda krizi sorunu çözmek için tek başına yeterli olmayabilir ama genetik mühendisliği yoluyla biyoteknoloji, hem çeşit iyileştirme ve geliştirme hem de hayvansal üretimin verimliliğini artırma potansiyelini sunarak, küresel gıda üretimini sürdürülebilir bir şekilde artırır. Biyoteknoloji, virüs, mantar ve böcek toleranslı çeşitler üreterek, genetik mühendisliği yoluyla, tarımsal kimyasalların kullanımını azaltarak maliyetlerin azalmasına ve çiftçiler için daha karlı üretimlerin yapılmasına olanak tanır.

Şu anda modern biyoteknoloji, genetik olarak değiştirilmiş organizmaların insan sağlığı, çevre, sosyo-ekonomik, etik ve kültürel konular açısından riskleri ve faydaları ile ilgili büyük kamuoyu tartışmalarıyla karşı karşıyadır. Ancak, modern tarımsal biyoteknolojilerin güvenli bir şekilde uygulanması, mevcut ve gelecekteki iklim değişikliğine uyum sağlayan yeni çeşitlerin elde edilmesine önemli ölçüde katkıda bulunmaktadır. Bunun sonucunda, gıda üretimi sürdürülebilirliğini veya gıdaya erişimi herkes için sağlamak ve gıda kaynaklarının küresel olarak verimli bir şekilde kullanılmasını sağlamak için tarımsal üretkenliği ve gıda güvenliğini büyük ölçüde artırmaktadır.

Yeşil biyoteknoloji, verimliliği artırmak, kimyasal girdilere olan bağımlılığı azaltmak ve çevresel sürdürülebilirliği geliştirmek amacıyla tarım, bahçecilik ve ormancılık alanlarında da kullanılan biyoteknolojik tekniklerin uygulanmasını ifade etmektedir.

Yeşil biyoteknoloji alanındaki son araştırmalar, ürün performansında önemli iyileştirmeler sağlayan ve tarımın en acil sorunlarına çözümler sunan yeni teknikler ortaya çıkarmıştır. Bu tekniklerden biri de, bitki genomlarında yüksek doğruluk ve verimlilikle hassas değişiklikler yapmayı sağlayan CRISPR (Clustered Regularly Interspaced Short Palindromic Repeats)/Cas9 gen düzenleme teknolojisidir. CRISPR, bakterilerin bağışıklık sisteminde bulunan, virüslere karşı genetik hafıza işlevi gören DNA dizileridir. Cas9 ise CRISPR ile birlikte çalışan bir enzimdir (*CRISPR-associated protein 9*). DNA'yı belirli bölgelerden kesme özelliğine sahiptir. Araştırmacılar, düzenlenmek istenen gen bölgesine uygun bir rehber RNA (sgRNA) tasarlarlar ve sonrasında bu rehber RNA, Cas9 enzimini DNA'nın hedeflenen noktasına yönlendirir. Cas9, DNA'da çift zincirli bir kesik (double-strand break) oluşturur. Hücre, bu kesilen bölgeyi kendi onarım mekanizmalarıyla tamir eder. Beklenen sonuç, dışarıdan verilen bu DNA parçası yardımıyla yeni genetik bilginin oraya eklenmesidir(knock-in).

CRISPR/Cas9 gibi araçlar kullanılarak yapılan gen düzenlemeleri ile çeşitlerin kurağa, sıcağa ve tuzluluğa olan dayanıklılığını arttırmak açısından ümitvar sonuçlar elde edilmektedir (Rai ve ark., 2023; Kanth ve ark., 2025; Sameen & Khalil, 2025). Özellikle buğday, mısır ve çeltikte, CRISPR/Cas platformlarının geleneksel moleküler ıslah ile entegrasyonunun, yüksek verimli ve strese dayanıklı çeşitlerin geliştirilmesini hızlandırdığı görülmüştür (Li ve ark., 2021). CRISPR düzenleme ile çeşit geliştirme süreleri kısaltılarak, iklime uyum sağlamış ve besin açısından zengin çeşitlerin üreticilere, dolaylı olarakda tüketicilere, daha hızlı ulaştırılması kolaylaşmıştır (Zhang ve ark., 2018; Williams ve ark., 2024). Yeni nesil dizileme ile, yabani akrabaların ve yeterince kullanılmayan türlerden elde edilen pan-genomik verilerin çalışmalara dahil edilmesi, CRISPR ile yapılacak iyileştirmeler için kullanılabilir allel gen çeşitliliğini daha da zenginleştirilmiş, ekolojik dengeyi bozmadan genetik çeşitliliğin genişlemesini sağlanmıştır (Zenda ve ark., 2021). CRISPR/Cas9 ile hastalıklara dirençli çeşitler gen mühendisliği yoluyla geliştirilerbilir, patojenlerin neden olduğu verim kayıpları azaltılabilir ve sentetik pestisitlere olan bağımlılık azaltılarak çevresel sürdürülebilirlik hedefleri güçlendirilebilir (Gan & Ling, 2022). Ek olarak, CRISPR ile kültür bitkilerinden, hektar başına daha yüksek verim ssağlanarak, daha az arazide ekim ile daha fazla üretim imkanı da elde edilebilir (Sameen & Khalil, 2025).

CRISPR/Cas aracılı düzenlemedeki son gelişmeler ile kuraklık, tuzluluk, sıcaklık ve diğer abiyotik streslere karşı gelişmiş tolerans gösteren çok sayıda hat üretilmiştir (Atia ve ark., 2024). Çoklu CRISPR/Cas9 platformları ile hem yapısal genler hem de bunların yukarı akış cis-düzenleyici elemanları hedeflenerek, çoklu strese karşı direnç sağlayan kantitatif gen lokuslarının oluşturulması sağlanabilmektedir (Nascimento ve ark., 2023). Son CRISPR/Cas9 çalışmalarından elde edilen deneysel kanıtlara göre, kuraklığa duyarlı lokusların düzenlenmesinin, tahıllarda kuraklığa olan töleransı belirgin şekilde artırdığını doğrulamaktadır (Rai ve ark., 2023). Araştırmacılar, CRISPR tabanlı düzenlemeleri genotipleme-sekanslama ve belirteç destekli seleksiyon ile birleştirerek, birden fazla strese dayanıklılığı sağlayan genlerin bitkilere aktarımını daha hızlı ve kolay hale getirmektedir (Villalobos-López ve ark., 2022). Özellikle tamamlayıcı pan-genom analizleri, yapay zekâ destekli seleksiyon yöntemleri aracılığıyla, ıslahta istenilen-örneğin kuraklığa dayanıklılık için-bitkilerin ortaya çıkma şansını arttırmakta ve kuraklığa dayanıklı allel havuzunu genişletmektedir (Razzaq ve ark., 2021). Bu nedenle, gen düzenlemeyi biyoinformatik ve yapay zeka araçlarıyla birleştiren entegre bir strateji, bu yenilikleri ölçeklendirmek ve uzun vadeli gıda tedariğini sağlamak için gereklidir. Ancak, bu ilerlemeleri yaygın tarım uygulamalarına dönüştürmek için teknik sınırlamalar ve düzenleyici zorluklar da ele alınmalıdır. Biyogüvenlik ile yeniliğe açık ve bilimsel temelli politikalar geliştirmek, CRISPR ile geliştirilmiş, kuraklığa ve tuzluluğa dayanıklı çeşitlerin yaygınlaştırılmasını hızlandıracak ve buğday, mısır ve soya fasulyesi için önemli iyileştirme potansiyelinden yararlanılmasını sağlayacaktır (Rabuma ve ark., 2024).

AI destekli yüksek verimli fenotipleme ile çoklu CRISPR stratejilerinin birleştirilmesi, ıslah döngülerini daha da kısaltabilir ve iklim dirençli kültür bitkilerinin dünya çapında erişilebilirliğini artırabilir (Wójcik-Gront ve ark., 2024). Gelecekteki araştırmalar, kuraklık, sıcaklık ve tuzluluk gibi birleşik baskıların altında verim istikrarını daha da artırmak için, çoklu CRISPR yaklaşımları yoluyla çoklu stres toleransı alellerinin biriktirilmesine öncelik vermelidir (Kaur ve ark., 2025).

Verim artırıcı ve kuraklığa dayanıklı aleller içeren CRISPR müdahaleleri, son zamanlarda yapılan gen düzenleme araştırmalarında vurgulanan üretkenlik ve iklim direnci gibi hedefleri karşılamaya hazırdır (Atia ve ark., 2024). Dahası, yapılan deneysel araştırmaların sonuçlarına göre, transgen içermeyen CRISPR düzenlemeleriyle elde edilen çeşitlerin, geleneksel çeşitlerle mukayese edilebilir bir tarımsal performans gösterdiği ve geleneksel çeşitlere göre daha fazla kuraklık toleransı gösterdiği bildirilmiştir (Karavolias ve ark., 2021). Deneysel araştırmaların sonuçları, CRISPR/Cas aracılı düzenlemelerin, DNA eklenmeden kuraklığa dayanıklı germplazmları hızla üretilebildiğini ve böylece hücre içi yapının bozulmadan kalarak buna uyum gösterdiğini bildirmiştir. (Kausar ve ark., 2022).

2. GIDA GÜVENİLİRLİĞİNİ AMAÇLAYAN YEŞİL BİYOTEKNOLOJİ MÜDAHALELERİNİN ETKİNLİĞİ, SOSYOEKONOMİK ETKİLERİ VE DÜZENLEYİCİ HUSUSLAR HAKKINDAKİ SON AMPİRİK BULGULAR

Şeffaf, uyumlu lisanslama prosedürleri ve kamu-özel sektör ortaklıkları yoluyla fikri mülkiyet engellerinin aşılması CRISPR teknolojisi için çok önemli olacaktır (Qaim, 2020). Bu nedenle, CRISPR kaynaklı elde edilen çeşitleri gıda güvenliği kazanımlarına dönüştürmek için, kamu araştırma kurumlarını, özel sektör firmalarını ve çiftçi örgütlerini bir araya getiren işbirliğine dayalı, fikri mülkiyet haklarına saygı duyan, birbiriyle uyumlu olan güvenli veri paylaşım platformlarının kurulması, bu tip kültür bitkilerinin izlenmesi için çok önemli olacaktır (Akinbo ve ark., 2025). CRISPR kaynaklı elde edilen çeşitleri geleneksel olarak yetiştirilen çeşitlerle benzer şekilde ele alan, küresel olarak uyumlu, bilime dayalı düzenleyici standartlar oluşturmak gerekir. Böylece insanların aklından geçen değişik çekincelerin cevabı verilirken, sürdürülebilir gıda sistemleri için bu bitkiler rahatlıkla kullanılabilir duruma getirilebilecektir (Gao, 2018; Ahmad ve ark., 2021). Genom düzenlemesi uygulanmış ürünler için mevcut güvenlik önlemlerini temel alan risk değerlendirme sistemleri, ekosistem, bitki sağlığı ve insan sağlığı üzerindeki uzun vadeli etkileri izleyebilmek ve gerektiğinde düzenleyici yasa veya yönergeleri güncelleyebilmek amacıyla kurumsal bir yapıya kavuşturulmalıdır (Lassoued ve ark., 2019). Algoritmik denetimlerin etkinliği için, bağımsız üçüncü taraf kurumlar; paydaş katılımını, ampirik zarar analizlerini ve bulguların şeffaf raporlanmasını içeren değerlendirmeleri yürütmekle yükümlü kılınmalıdır (Costanza-Chock ve ark., 2022). Bu yönetişim yapılarının bütünlüğünü korumak ve veri yönetimini desteklemek için kamu fonlama mekanizmalarının tahsis edilmesi gerekli olacaktır (Williamson ve ark., 2021).

Avrupa Birliği'nin GDO mevzuatı küresel ticaretin önünde engel oluşturmaktadır. (Jiang, 2019; Turnbull ve ark., 2021; Jones ve ark., 2022). Rekombinant DNA sınıflandırmalarını atlatan ve transgen içermeyen CRISPR stratejileri, bu engelleri azaltarak onay süreçlerini hızlandırabilir ve olumsuz iklim koşullarına dirençli bitkilerin yaygınlaşmasını kolaylaştırabilir (Tripathi ve ark., 2022; Saikia ve ark., 2024).

Genetiği değiştirilmiş (GDO) bitkilerin dijital ikiz modellerinin blockchain ve FAIR (Findable, Accessible, Interoperable, Reusable) veri platformlarıyla entegrasyonu (Safdar ve ark., 2024), tarla ölçeğinde genotip–çevre etkileşimlerinin simülasyonunu mümkün kılarak, hem biyoteknolojik müdahalelerin izlenebilirliğini hem de verim ve kaynak kullanımının optimizasyonunu desteklemektedir (MacPherson ve ark., 2022). Bu entegre altyapılar, çeşit verimliliğini istikrarlı kılmakta, sera gazı emisyonlarını azaltmakta ve küçük çiftçilerin sosyoekonomik durumunu iyileştirmektedir. Ayrıca denetlenebilir veriler, sürdürülebilir kalkınma hedefleri (SDG 2, SDG 13, SDG 12, SDG 9) doğrultusunda gerçekleşen ilerlemelerin yüksek hassasiyetle takip edilmesini sağlamaktadır (Dhal & Kar, 2024 (Parra-López ve ark., 2024; Rajput ve ark., 2025). Gelecekte yapılacak deneysel değerlendirmeler, bu teknolojilerin farklı agroekolojik bölgelerde maliyet–fayda dengelerini gözönüne alarak sürdürülebilir uygulamalara olumlu yönde katkı sunacaklardır (Chaterji ve ark., 2020; Sridhar ve ark., 2023; Hong & Xiao, 2024).)

3. SONUÇ

Yeşil biyoteknoloji, tarımda küresel sorunlara çözümler sunarak, değişen iklim koşullarında sürdürülebilir gıda sistemleri arayışında bir araç görevi görmektedir. Çeşitli iklimlerde biyoteknolojinin başarılı uygulamaları, bölgesel tarımsal zorlukları etkili bir şekilde ele alarak ve artan küresel nüfus için gıda kaynaklarını güvence altına alarak, biyoteknolojinin tarım ve gıda için ne kadar önemli olduğunu göstermektedir. Yeşil biyoteknoloji, sağladığı faydalara rağmen, genetiği değiştirilmiş organizmalar (GDO'lar), genetik kaynaklar üzerindeki fikri mülkiyet hakları ve uzun vadeli ekolojik etkiler konusunda tartışmalara yol açmaktadır. Güvenli ve sorumlu bir uygulama sağlamak için düzenleyici yasalar ve halkın fikirlerini açıkça söylemesi büyük önem taşımaktadır. CRISPR-Cas gen düzenleme, sentetik biyoloji ve biyoinformatik alanındaki gelişmelerin yeşil biyoteknolojiye devrim getirmesi beklenmektedir. Biyoteknoloji ile birleştirilen hassas tarım ekolojik uyumu teşvik ederken, aynı zamanda son derece dayanıklı çeşitler yaratabilir. Uygun fiyatlı, kullanıcı dostu dijital araçları yaygınlaştıran ve yaygınlaştırma kapasitesini güçlendiren politika çerçeveleri, yapay zeka ile geliştirilmiş yeşil biyoteknolojinin iklim dostu potansiyelini tam olarak ortaya koyması için çok önemlidir (Yang & Sun, 2024). Dünya genelinde uyumlaştırılmış düzenleyici standartlar ve sınır ötesi veri paylaşım protokollerinin sağlanması, AI destekli yeşil biyoteknoloji çözümlerinin tam ölçeklenebilirliğini ortaya çıkarmak için çok önemli olacaktır (Gartland & Gartland, 2016). Gen düzenleme okuryazarlığını katılımcı saha denemeleriyle birleştiren hedefli kapasite geliştirme girişimleri, eğitim eksikliklerini giderebilir, çiftçileri güçlendirebilir ve DNA içermeyen, iklime dirençli çeşitlerin sahada benimsenmesini hızlandırabilir (Parra-López ve ark., 2024).

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THE PEA (*Pisum sativum L.*) AS A FUTURE SOURCE OF PLANT PROTEIN AND INDUSTRIAL RAW MATERIAL: MULTIFACETED APPLICATIONS AND ECONOMIC TRANSITION

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1. INTRODUCTION

Pea (*Pisum sativum* L.) is an annual, herbaceous, dicotyledonous plant species belonging to the subfamily *Papilionoideae* of the *Fabaceae* family (Zhang et.al., 2015) Cultivated peas originated in a broad geographic area extending from Western and Southwestern Asia to Europe and have been utilized as a significant food source since antiquity (Bagheri et al., 2023). Morphologically, the stem is generally climbing or semi-vining, with the plant height varying between 15 and 200 cm, depending on the cultivar (Daba et al., 2025).The leaves are compound, consisting of 1−4 pairs of leaflets, and include branched tendrils that enable the plant to cling and climb. The flowers are borne in racemes, exhibiting the typical legume form and are hermaphroditic, primarily undergoing self-pollination (Fahmi et al., 2019). The rate of cross-pollination is low, typically around 1%–%2, depending on the environmental conditions. The fruit is a pod, having a rectangular-linear structure that contains 3 to 10 seeds. The seeds are spherical, either smooth or wrinkled, and vary in color and size across different cultivars (Aluko et al., 2015).

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P.sativum is a cultivated plant that prefers cool and humid climate conditions; a daily average temperature range of 15^0C to 21^0C is optimal for development, and the plant is sensitive to freezing temperatures. Agronomically, it holds a critical role in crop rotation systems by enriching the soil's nitrogen content through its ability to fix atmospheric nitrogen via the nodules on its roots (Fahim et al., 2019)

It is a nutritionally rich legume, containing high proportions of protein (approximately 6.3%), carbohydrates (around 14.4%), fiber, starch, and sugars. Furthermore, it is abundant in essential nutrients, including Vitamins A and C, the Vitamin B complex, and important minerals such as iron, phosphorus, and potassium (Kumari et al., 2021). All these characteristics make the pea not only a valuable vegetable for human nutrition but also a privileged model organism in the history of science, having been utilized by Gregor Mendel in his pioneering heredity studies that laid the foundations of genetics (Han et al., 2019).

The world faces complex challenges such as meeting the nutritional needs of a growing population, mitigating the effects of climate change, and utilizing limited natural resources more efficiently (Santos et al., 2019). Under these global pressures, the shift of food systems and industrial raw materials towards sustainable and innovative sources has become a necessity. In this context, peas (*Pisum sativum* L.), an ancient and widespread member of the legume family, are being rediscovered as a versatile crop with a critical role for both nutritional security and the bioeconomy (Jenkis et al., 2021).

Peas are one of the oldest domesticated crops, with a cultivation history dating back to 7000 B.C. Starting in the Middle East and rapidly spreading to Europe and Asia, this historical journey demonstrates the pea's indispensable position as a critical source of protein, fiber, vitamins, and minerals in human nutrition (Fahmi et al., 2019). However, the consumption of legumes saw a decline in the second half of the 20th century as animal protein and cereals took precedence. (Thakur et al., 2019). Today, the importance of peas as a high biological value plant-based protein source is rapidly increasing, especially with the rise of healthy eating trends and growing interest in plant-based diets. Pea protein is particularly rich in essential amino acids like lysine and arginine, making it complementary to cereal proteins (Naghshi et al., 2018). These characteristics establish peas as one of the cornerstones of vegetarian, vegan, and flexitarian dietary trends.

The value of the pea in agricultural systems is not limited to the harvested product alone; it also stems from its significant contributions to environmental sustainability (Kan et al., 2018). As a legume, the pea has the ability to fix atmospheric nitrogen into the soil through Rhizobium bacteria in its roots. This process of biological nitrogen fixation reduces the need for synthetic nitrogen fertilizers, thereby lowering farming costs and minimizing the greenhouse gas emissions caused by nitrogen fertilizer production (Gao et al.,2022). Furthermore, peas are an excellent precursor crop for rotation in common agricultural practices; they improve soil health, reduce erosion, and support biodiversity. These ecological benefits make the pea an indispensable component of modern regenerative agriculture and climate-smart farming strategies (Devi et al., 2019).

Peas (*Pisum sativum* L.) have transformed from a simple legume traditionally consumed as fresh or dried food into a strategic raw material for modern food and industrial sectors. Its nutritional content, environmental benefits, and processing flexibility have made the pea not only a crop that supports food security but also a component central to the goals of the circular economy and sustainable production (Wang et al., 2010). This article comprehensively examines the multi-purpose potential of the pea, specifically its role in the economic and environmental transformation as the plant-based protein and industrial raw material source of the future (Yu et al., 2020).

2. THE PEA AS THE PLANT-BASED PROTEIN OF THE FUTURE

The growing world population and the awareness of the environmental burden of animal protein sources have rapidly increased the demand for plant-based proteins. Peas are playing a leading role in this global shift. Today, in line with global food security and sustainability goals, the importance of high-nutritional-value plant proteins as alternatives to animal protein sources is continuously rising. In this context, the pea (*Pisum sativum* L.), a member of the *Fabaceae* family, is positioned as a key crop with the potential to be the plant-based protein source of the future due to its superior agronomic and nutraceutical properties. Pea seeds contain approximately 20% to 30% protein by mass, depending on the variety, an amount significantly higher than the protein content of cereals, offering an effective alternative to animal sources (Ren et al., 2021). Pea protein is rich in certain essential amino acids, such as lysine, which are vital for human metabolism, but may be limited in methionine and cysteine. This characteristic ensures an ideal protein balance when consumed in combination with cereals, which are rich in methionine (Ge et al., 2020).

The pea's contribution to agricultural sustainability is one of the most important factors distinguishing it from traditional protein sources. As a legume, P. sativum has the ability to fix atmospheric nitrogen into the soil through the symbiotic nitrogen fixation carried out by Rhizobium bacteria in its roots (Wang et al., 2010). This characteristic helps to reduce the need for synthetic nitrogen fertilizers, thereby lowering production costs while minimizing environmental nitrogen pollution and the agricultural carbon footprint (Shantakumar et al., 2022). Furthermore, the pea is a critical component in crop rotation systems, where it improves soil health and structure and supports biodiversity.

The industrial isolation and purification of pea protein have enabled the production of highly functional food ingredients in the form of protein concentrates and isolates (Liu et al., 2018). These isolates are used as essential inputs in the formulation of a wide range of products such as meat alternatives (plant-based meat), dairy alternatives, nutritional supplements, and sports nutrition products due to their superior solubility, emulsification, gel-forming, and water-holding capacities (Langyan et al., 2022).

The pea is poised to play a central role in the future of global food systems, not only through its high protein content and valuable amino acid profile but also because of its biological nitrogen fixation ability, which supports environmentally friendly cultivation practices. The rise of sustainable food production and healthy eating trends will further solidify the use of pea protein as a strategic raw material in innovative food technologies. This situation is permanently strengthening the pea's position in the literature of nutritional science and agricultural economics.

2.1. Characteristics That Highlight Pea Protein's Prominence

High Nutritional Value and Digestibility: Dry peas contain 20-25% high-quality protein by weight. They are rich in essential amino acids such as lysine and arginine. The fact that pea protein contains a lower amount of methionine compared to animal sources allows for a balanced amino acid profile when mixed with other protein sources, such as cereals (Naghshi et al., 2018).

Non-Allergenic and Functional Properties: Since pea protein does not contain common allergens like soy and gluten, it is a safe alternative for individuals with food allergies. Furthermore, its functional properties such as high emulsification, gelling, and foaming capabilities make it an ideal ingredient for food formulations (Ewy et al., 2022).

Sustainability: The pea plant fixes atmospheric nitrogen into the soil through Rhizobium bacteria located in its roots. This natural nitrogen fixation reduces the need for synthetic fertilizers, increases soil fertility, and lowers the carbon footprint of agriculture. This characteristic makes pea protein an environmentally responsible choice (Chung et al., 2012).

2.2. Production of Protein Isolate and Concentrate

The production of Pea Protein Isolate (PPI) and Pea Protein Concentrate (PPC) represents a critical process chain that enables the transformation of Pisum sativum seeds into high-value-added ingredients for the food and nutraceutical industries(Chen et al.,2021). These processes aim to maximize the pea's high protein content (20%–30%) by preserving its functional properties and purifying it from unwanted components.The most valuable protein forms of peas are Pea Protein Isolate (PPI) and Concentrate. These products are obtained from dried pea seeds using wet and dry fractionation methods. Isolates have a protein purity exceeding 85%, while concentrates contain 50-80% protein (Abdal-Aal et al., 2019).

These high-purity products are widely used in the following areas:

Vegan and Vegetarian Foods: Plant-based meat alternatives (burger patties, sausages, ground meat), dairy analogs (cheese, yogurt), and protein drinks.

Sports Nutrition: Protein powders, energy bars, and ready-to-drink beverages.

Functional Foods: Nutritional supplements, fortified snacks, and specialized diet products (Shantakumar et al., 2022).

3. INDUSTRIAL USES OF PEAS

Peas are not just a protein source; the other components they contain (starch, fiber, fat) also create value as a versatile raw material in various industries. Pea has become a strategic legume with increasing economic value due to its versatile use in modern food processing and industrial sectors, extending beyond traditional food consumption (Ye et al.,2022). The industrial applications of the pea are primarily based on the high functionality of the protein, starch, and fiber components derived from its seeds. These components facilitate the production of value-added products across a wide range, from the food industry to the feed sector (Wojdylo et al., 2020).

Peas have transformed from a simple legume into a critical bio-raw material source for modern industrial and food systems, thanks to their high content of protein, starch, and fiber. In the industrial sector, pea seeds are primarily processed using wet and dry fractionation methods to separate them into high-purity components (Raghunathan et al., 2022). The resulting Pea Protein Isolates (PPI) and Concentrates (PPC) play a key role in food formulations due to their superior emulsification, gelling, and water-holding capacities. These components are used as fundamental building blocks in vegan meat alternatives, dairy analogs, sports nutrition products (protein powders and bars), and functional foods, primarily to meet the growing demand for plant-based diets (Ge et al., 2020). Furthermore, pea starch, with its high amylose content, is used in diet foods and as a texturizing agent, while by-products such as pea hulls contribute to the circular economy in the production of animal feed and new protein concentrates.

Beyond these core food applications, the industrial uses of the pea extend outside the nutritional sector. Its high protein content and non-allergenic nature have made pea protein an appealing ingredient for the cosmetics industry, where it acts as a moisturizing and reparative agent in hair and skin care products. It is also increasingly utilized in the animal feed and pet food sectors as a protein and energy source, specifically as a sustainable alternative to soy and fishmeal (Dahl et al., 2012). This multi-purpose transformation potential moves the pea beyond merely a crop supporting food security, positioning it as a strategic component of a sustainable bioeconomy model committed to the efficient use of limited resources and a low carbon footprint (Chung et al., 2012).

3.1. Isolation and Formulations in the Food Industry

The most significant industrial use of peas is the production of pea protein isolate (PPI) and concentrate (PPC). These protein fractions are obtained by dry milling the pea seed, followed by wet processing techniques like aqueous extraction, pH adjustment, and drying (Arif et al., 2020). High-purity PPI (protein content of 80% and above) has superior emulsification, water, and oil-binding capacities. These functional properties have made PPI an indispensable raw material in the following areas:

Meat Analogues and Vegan Products: Pea protein is the fundamental structural component of meat substitutes—such as plant-based burgers, sausages, and ground products—due to its texture and nutritional profile. The isolate's ability to form gels and fibrous structures is critical in mimicking the chewiness and structure of animal meat.

Dairy Alternatives: Pea protein hydrolysates and isolates are used as protein supplements and stabilizers in non-dairy beverages, yogurts, and cheese analogues.

Functional Foods and Nutritional Supplements: Due to its high biological value amino acid profile, it forms the basis of nutraceutical products, such as protein powders and nutrition bars used in sports nutrition (Avezum, 2022).

Pea starch is another important product in the food industry. Pea starch contains a high proportion of amylose (approximately 30%–60%) compared to other common starch sources (corn, wheat). This high amylose content gives the starch strong gelling and retrogradation (gel hardening) properties. These characteristics make it valuable as a texturizer and stabilizer in noodles, clear gels, and certain baked goods (Chen et al., 2021).

3.2. Non-Food Industrial and Agricultural Applications

The industrial use of peas is not limited to the food sector. By-products from pea processing, such as hulls and seed coats, are valuable as a rich source of dietary fiber. These fibers are used as bulking agents and components to support gut health in products like bread, breakfast cereals, and nutritional supplements (Languan et al., 2022). Furthermore, residues left over from processing the pea seed and lower-grade peas are used as a cost-effective alternative to traditional feed raw materials like soybean and corn in animal feed formulations, particularly in poultry and swine rations, due to their high protein and energy content (Ye et al., 2022). Agriculturally, the pea's capability for biological nitrogen fixation naturally enriches the soil's nitrogen content, sustaining its role as an indispensable precursor crop in organic and sustainable farming systems. These multi-faceted industrial and environmental benefits position P. sativum as a commodity of strategic importance in global supply chains, open to innovative applications (Kumari et al., 2021).

3.3. Starch and By-products

Pea starch is a significant product used in both food and non-food industries. The starch's content of amylose and amylopectin grants it distinct functional properties.

Food Industry: Due to its low gelatinization temperature and high gel strength, pea starch is used as a thickener, gelling agent, and stabilizer in products like sauces, soups, and puddings.

Bioplastic Production: Bio-polymers derived from pea starch are a potential raw material source for the production of biodegradable plastics. These bioplastics offer a sustainable alternative to petroleum-based plastics in products such as single-use packaging, utensils, and agricultural films (Naghshi et al., 2018).

3.4. Fiber and Feed Industry

By-products obtained during the pea processing chain also hold economic value.

Dietary Fiber: Pea hulls and the pulp remaining after protein extraction contain a high level of insoluble dietary fiber. This fiber is used in functional foods, bread, snacks, and dietary supplements, supporting digestive health.

Animal Feed: Residues left after protein and starch extraction are utilized as a valuable protein and energy source in animal feed formulations, especially for poultry and cattle. This contributes to the sustainability of the livestock sector by reducing feed production costs (Thakur et al., 2019).

4. ROLE IN ECONOMIC AND ENVIRONMENTAL TRANSFORMATION

The multipurpose use of peas has a transformative effect on the agricultural economy and the global food system.

- *Economic Value Addition:* The processing of peas not only as food but also into high-value-added products (protein isolate, starch) opens new revenue streams for farmers and contributes to the development of the agro-industry.

- *Environmental Sustainability:* When used in crop rotation systems, peas improve the biological structure of the soil and reduce dependence on synthetic fertilizer. This protects the agricultural ecosystem and plays a significant role in combating climate change.

- *Food Security and Diversity:* By offering a sustainable alternative to animal proteins, it helps close the global protein gap. Furthermore, it increases food diversity for individuals with allergies and consumers on specialized diets.

In this era where global food systems are under pressure for sustainability, peas (Pisum sativum L.) are emerging as a strategic commodity that both supports economic development and mitigates environmental impacts. The pea's role in this transformation stems from the combination of its biological and agronomic characteristics with modern industrial demands.

4.1. The Pea in Economic Transformation

The economic significance of the pea is primarily based on the value chain it creates in the agriculture and food industries. The dried pea seed, which is rich in protein, starch, and fiber, is a key raw material particularly driving the plant-based protein market.

- *Creation of New Food Markets:* The production of pea protein isolate and concentrate forms the basis of high-margin markets like the rapidly growing meat substitutes (plant-based meat), dairy alternatives, and sports nutrition sectors. This encourages an economic shift from the traditional model of agricultural commodity trade toward a high-tech food processing and formulation industry (Ewy et al., 2022).

- *Diversification of Farmer Income:* Peas can command higher market prices than cereal production in many regions. Furthermore, its short growth cycle and low cultivation costs especially due to savings on nitrogen fertilizer make it a profitable crop rotation plant for farmers. This improves the economic resilience and risk management of agricultural businesses.

- *Industrial Efficiency:* The high amylose content of pea starch provides specific functional properties (strong gelation) in the food processing industry, increasing efficiency in starch-based production and enabling the development of innovative products (Santos et al.,2019).

4.2. The Pea in Environmental Transformation

The positive environmental impacts of the pea enable it to take on a vital role in combating global climate change and soil degradation. These effects primarily stem from its contributions to sustainable agricultural practices.

- *Biological Nitrogen Fixation and Carbon Footprint:* Pisum sativum fixes free atmospheric nitrogen into the soil through its ability for symbiotic nitrogen fixation. This natural process significantly reduces the need for nitrogen fertilizers for subsequent crops. Nitrogen fertilizer production is one of the largest sources of greenhouse gas (GHG) emissions in the agricultural sector, due to its high energy requirement (Wojdylo et al., 2020). The use of peas directly lowers these emissions, markedly improving the carbon footprint of agricultural production.

- *Soil Health and Biodiversity:* The use of peas in crop rotation improves the soil's structure, organic matter content, and water-holding capacity. Their root systems help prevent soil erosion (Jenkis et al., 2021). Additionally, they support agricultural biodiversity by creating a more varied farming ecosystem compared to traditional monoculture systems.

- *Water Use Efficiency:* Certain drought-tolerant pea varieties increase water use efficiency by reducing irrigation requirements, which is especially important in regions with limited water resources (Kan et al., 2018).

5. CONCLUSION

The pea has moved beyond being a traditional food product to secure a strategic position as a versatile industrial raw material and a sustainable protein source. Advancements in industrial processing technologies have maximized the value of pea protein, starch, and fiber. This transformation has not only created new economic opportunities but also presented a model that reduces the environmental impact of agriculture and strengthens global food security. In the future, accelerating research in pea breeding and processing technologies will further enhance the potential of this valuable plant, ensuring it continues to play a key role in building a sustainable food and industrial system. Consequently, peas are not only a highly nutritious product but also a central tool for achieving the goals of the circular economy and climate-smart agriculture. The combination of economic incentives with gains in environmental sustainability makes it an indispensable component of future food and agricultural policies.

This article has comprehensively examined the multifaceted role of the pea plant as the plant-based protein and industrial raw material of the future, offering innovative solutions to the sustainability and nutritional challenges faced by global food systems, thanks to its high protein content and superior functional properties. Our primary objective was to demonstrate, from an academic perspective, the economic and environmental transformation created by the pea through modern industrial processes and environmentally friendly agricultural practices, moving beyond its role as merely a traditional legume.

The findings clearly highlight the scope of the benefits and potential gains provided by the use of peas. The most significant gain is the prominence of pea protein isolate (PPI) and concentrate (PPC) as core ingredients in meat and dairy alternatives within the rapidly growing plant-based food market. This directly contributes to global efforts to strengthen protein supply security while mitigating the environmental impact associated with animal husbandry. Environmental gains include the pea's ability to reduce dependence on synthetic nitrogen fertilizers thanks to its biological nitrogen fixation capability and the resulting decrease in the agricultural carbon footprint. Furthermore, its role in crop rotation systems offers a critical agronomic benefit for maintaining soil health and biodiversity. Economically, the pea has the potential to increase income diversity and profitability in the agricultural sector through high-value-added PPI and starch products.

However, the pea's role in this transformation is accompanied by certain challenges and drawbacks. Industrially, the high water and energy consumption of wet fractionation methods used in PPI and PPC production is a disadvantage that may conflict with environmental sustainability goals. Additionally, the naturally low content of sulfur-containing amino acids (methionine and cysteine) in pea protein necessitates complementary blending with other protein sources (such as cereals) to create a balanced amino acid profile in some nutritional formulations. Finally, the pea's susceptibility to pests and diseases (particularly powdery mildew and root rot) is a major agronomic limitation that affects yield stability and farmer risk.

In summary, the pea, with its high protein and functional starch content, holds a strategic position in the future of the food industry. Its unique contributions to environmental sustainability place it at the center of nutritional and agricultural economic transformation on a global scale. Future research should focus on increasing the plant's production efficiency, minimizing the environmental impact of wet processing, and genetically improving its amino acid balance. The pea, with its clear benefits and notable limitations, will maintain its importance as an indispensable solution in the search for a sustainable protein source.

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SPECIFIC ALFALFA PATHOGENS

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1. INTRODUCTION

Alfalfa (*Medicago sativa* L.) is vital to farming, as it is highly nutritious and benefits the environment in numerous ways. It has more crude protein and digestible energy than other fodder crops (Yang et al., 2022). Rhizobium bacteria convert atmospheric nitrogen into a form that plants can use in root nodules, thereby improving soil fertility and reducing the need for synthetic nitrogen fertilisers. This is good for sustainable production, both economically and environmentally (Buzzanca et al., 2023).

Alfalfa is an important crop for farmers, but it suffers from reduced output and quality due to various diseases. These diseases can affect various parts of the plant, including the flowers, leaves, roots, and stems. They reduce photosynthesis efficiency, making it difficult for the plant to obtain water and nutrients, and cause the plant to react to stress (Yang et al., 2022). These changes render fodder less nutritious by reducing its dry matter, protein, energy, and digestible fibre content (Putnam, 2021).

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The most frequent diseases that affect alfalfa are anthracnose, mildew, powdery mildew, rust, leaf spots, root rot, and wilt. These diseases kill seedlings early, diminish yields, and make the plant canopy less dense. Some diseases produce chlorosis by creating spots on the leaves and stems. This causes the leaves to fall off, resulting in a decline in both the crop's quality and quantity.

2. FUNGAL DISEASES IN ALFALFA

2.1. Root Diseases of Alfalfa

2.1.1. Rhizoctonia Root Rot (*Rhizoctonia solani* Kühn. (synonym: *Thatephorus cucumeris* [FR] Donk):

Symptoms and Damage: Rhizoctonia spp. Causes root, crown, shoot and leaf rot in alfalfa, particularly under conditions of high temperature and high soil moisture. Infection usually begins at the primary root, and dark-edged elliptical lesions form on the root surface. During the crown rot stage, brown spots appear on young shoots and seedlings, and these tissues eventually die. Sunken, light brown lesions are prominent at the base of the stem. In advanced infections, plants exhibit stunted growth, wilting, yellowing (chlorosis), and root rot. Seedling mortality increases under high temperature and moist soil conditions. *Rhizoctonia solani* AG-4 isolates, in particular, are highly pathogenic and cause wet, longitudinal root lesions, as well as the formation of sclerotia (resting structures). These sclerotia can germinate under suitable conditions and cause new infections (Stuteville and Erwin, 1990; Ajayi-Oyetunde and Bradley, 2018).

Management: There is no effective chemical control method against the disease. However, alfalfa varieties with strong root systems and tolerance are recommended. Good soil drainage, avoiding frequent watering, and protecting fields from waterlogging reduce the risk of infection. As *R. solani*, the causative agent of the disease, can survive in the soil for many years in the form of sclerotia, crop rotation (especially with non-leguminous plants) and the destruction of infected plant debris are of great importance. In addition, as the disease spreads rapidly at suitable soil temperatures (28–32 °C) and humidity (%80–95%), cultural measures should be taken to reduce these conditions (ul Haq and Ijaz, 2021).

2.1.2. Violet Root Rot (*Rhizoctonia crocorum*)

Symptoms and Damage: *Rhizoctonia crocorum* DC. Ex Fr. (sexual stage *Helicobasidium purpureum Pat.*) can survive in soil as tiny black sclerotia or as a saprophyte on decomposing plant debris (Duggar, 1915; Gamell, 1949). The sickness usually occurs in organic-rich, moist, poorly drained soils, but it can also occur in well-drained areas (Hull and Wilson, 1946). Older plants, waterlogged areas, and plants with root injury are more likely to get infections in midsummer (Stuteville and Erwin, 1990). Infected plants are lighter and browner than healthy ones. Typical symptoms include brown staining, softening, and the development of a dense, purplish or cinnamon-colored mycelial layer on the roots that may reach 20 cm into the soil (Stuteville and Erwin, 1990). The root tissue completely deteriorates, becomes fibrous, and develops black sclerotia (Naseri, 2002). Affected plants may show chlorosis, early wilting, and sudden death. In afflicted areas, healthy and infected plants have distinct brown boundaries (Chen and Page, 1999). Genetic analysis has shown that this disease is related to Helicobasidium species (Uetake et al., 2002). The illness is common in late summer and early fall (Stuteville & Erwin, 1990; Alptekin and Erol, 2004).

Management: Chemical treatment for violet root rot is rarely effective or cost-prohibitive (Pandey et al., 2025). Thus, crop rotation and cultural approaches work best. Grow crops in well-drained, low-moisture areas and exclude sensitive plants (Cheah and Page, 1999). Rotate with non-host plants, such as Trifolium species, Lotus corniculatus, cereals, and maize, since the disease survives in the soil for a long time. Acidic soils lose inoculum density after liming and deep ploughing (Hull and Wilson, 1946). Alfalfa is more resilient and disease-resistant when mowed before flowering (Stuteville and Erwin, 1990). Without proper cultural measures, the illness may reduce agricultural yields.

2.1.3. *Fusarium* spp.

Symptoms and Damage: *Fusarium* species are soil-borne diseases that mostly attack plant roots. The species *F. oxysporum*, *F. solani*, *F. moniliforme*, and *F. avenaceum* are the most virulent pathogens affecting alfalfa. These fungi can persist in the soil for extended durations as chlamydospores, mycelial pieces, and spores (micro- and macroconidia). Chlamydospores are remarkably resilient and can persist in soil for decades. Chlamydospores germinate under appropriate environmental circumstances in response to organic materials (sugars, amino acids) present in alfalfa root exudates. The resultant hyphae infiltrate the root and stem tissues either directly or via injuries. This results in brown-black necrotic lesions in the root cortex and vascular tissue obstructions. The plants exhibit wilting, chlorosis, and root decay. In advanced stages, the root cavity depletes, lateral roots decay, and the plant deteriorates. The disease is more common in warm soils; nevertheless, its occurrence has diminished relative to the past owing to the emergence of resistant varieties.

Management: Fusarium spores can persist on contaminated plant waste or seeds, facilitating the disease's transmission to healthy regions. Damage is most pronounced in plants experiencing environmental stress.

2.1.4. Verticillium wilt (*Verticillium albo-atrum*)

Symptoms and Damage: Verticillium wilt is a significant vascular disease of alfalfa (Medicago sativa L.) caused by the dark-myceliated fungus *Verticillium albo-atrum*, currently classified as *V. alfalfae* (Xu et al., 2019). In the initial phases of the disease, the leaflets exhibit V-shaped chlorotic lesions (Figure 1), with the tips desiccating and altering to hues of pink, orange, or brown (Christen and Peaden, 1981). The leaves flex or contort, the stems remain verdant, whilst the lignified tissue becomes brown. In subsequent phases, the roots begin to sag, exhibit slow growth, lose leaves, and change in colour. The disease impairs the plant's metabolism by hindering its ability to photosynthesise and transport water. In severe infections, yield loss may reach 50% (Phillippe, 1991). The quality of the feed diminishes due to reduced dry matter, protein, and digestible fibre (Putnam, 2021).

Figure 1. Typical symptoms of *Verticillium* disease on alfalfa leaves (Erwin and Howell, 1998)

Management: The disease can spread by contaminated seeds, plant debris, straw, manure, wind, water, agricultural equipment, and insects (Phillippe, 1991). The pathogen can persist on the seed surface and in its tissues (Xu et al., 2019). Control is achieved by growing resistant plants, using healthy seeds and materials, and keeping the farm clean. Sanitise and disinfect instruments before sowing. Transitioning from contaminated fields to clean ones requires vigilance. Alternating crops with non-host plants reduces inoculum for 2 years. Seed fungicides, weed control, and preventing contamination are also useful disease management methods (Xu et al., 2019).

2.1.5. Root Rot and Stem Rot (*Sclerotinia trifoliorum*)

Symptoms and Damage: *Sclerotinia* root and stem rot is a serious disease that affects alfalfa and other leguminous forage crops, especially when the weather is cool and wet. The first signs are that the stem parts near the soil surface look water-soaked, become yellow, and wilt. A white, cottony mycelial layer grows on the stem as the sickness worsens, and the tissues soften and fall apart. Most of the time, sick plants wilt and die from the top down. The pathogen can survive the summer months in the soil or on plant detritus because black, hard, irregularly shaped sclerotia develop on the mycelium layer (Alptekin and Erol, 2013).

Management: Chemical control usually doesn't work because the disease can live in the soil for a long time. Cultural control is the best way to do this. Deep ploughing deposits sclerotia in lower soil layers, thereby preventing the production of apothecia and the spread of spores. To let more air in and prevent too much moisture from building up, crop leftovers should be removed in the fall. Crop rotation and using disease-free seeds from farms that have been afflicted also help stop the spread of illness. Some fungicide tests have been successful, but a long-lasting, inexpensive chemical remedy has not yet been developed (Alptekin and Erol, 2013).

2.1.6. Pythium Seed Rot, Damping-off and Root Rot

Symptoms and Damage: *Pythium* species injure alfalfa seeds and seedlings, especially in heavy, moist soils. Some species cause seed rot, damping-off, and root rot. If soil moisture is sufficient, resting spores (sporangia) form zoospores that infect healthy roots (Johnson, 1968). After infection, seedlings thin, wither, and die at the root collar before and after emergence. Root tips have brown necrotic patches, and the rot spreads up the stem to the base. Field stunting, withering, and thinning increase with the illness (Umar et al., 2022). There are over 200 Pythium species worldwide. *P. ultimum*, *P. irregulare*, *P. aphanidermatum,* and *P. coloratum* cause most alfalfa root rot. These variables cause root tip necrosis, main root browning, and inhibition of plant development (Berg et al., 2017; Zhang et al., 2021).

Management: It is crucial to apply systemic fungicides to seeds to manage *Pythium* infections. Achieving equilibrium fertilization, maintaining optimal soil pH, and ensuring soil aeration are important in controlling this disease (Stuteville and Erwin, 1990).

2.1.7. Aphanomyces Root Rot

Symptoms and Damage: Aphanomyces root rot is common in poorly drained soils that retain water, and it can kill young plants by preventing root growth. Infected seedlings show yellowing (chlorosis) and slow leaf development. The roots turn brown, the secondary roots start to rot, and the number of nodules decreases. People may mistake the sickness for a lack of nitrogen (Malvick, 2002).

Management: Managing the disease requires making sure that the soil drains well and that the water level is balanced. It is best to choose alfalfa cultivars that are resistant to Aphanomyces euteiches Race 1 and Race 2. In areas with infections, crop rotation should be with non-leguminous crops. Seed treatment or coating technologies can also protect seeds from chemicals (Stuteville and Erwin, 1990; Malvick et al., 2002).

2.2. Leaf Diseases

2.2.1. Powdery Mildew on Alfalfa (*Leveillula tauricva* (Lev) Arn)

Symptoms and Damage: The illness typically manifests on leaves in regions with inadequate air circulation and in shady environments. The upper and lower surfaces of diseased leaves and the upper portion of the stem are coated with a white, powdery covering resulting from the pathogen's *mycelium* **(Figure 2)**. These regions are replete with conidia and cleistothecia. Initially, yellow dots appear on the leaves, which subsequently develop into an ash-coloured fungal layer. It may manifest on the undersides of sun-exposed leaves or on both surfaces of shaded leaves. Juvenile foliage is especially vulnerable to the affliction. Infected leaves ultimately curl, wither, and abscise prematurely (Onar, 2005).

Management: Given that the infection persists in buds during winter, it is crucial to utilize resistant types, conduct spring pruning, and eliminate and incinerate infected shoots. The application of sulphur-based formulations is advised for chemical control (Umar et al., 2022).

Figure 2. Powdery mildew disease in alfalfa (Umar et al., 2022)

2.2.2. Leptosphaerulina Leaf Spot (*Leptotrochila medicaginis* (Fuckel))

Symptoms and Damage: The disease usually begins with small, circular spots on the leaves, ranging from light to dark brown. The leaf tissue around the spots gradually turns yellow, and premature leaf drop occurs. Lesions may then progress towards the stems and petioles. Cool, moist conditions encourage disease development. Severe infections increase leaf drop in plants, reducing photosynthetic area, lowering dry matter yield, and negatively affecting forage quality (Stuteville & Erwin, 1990).

Management: To control the disease, it is recommended to choose resistant varieties, avoid sprinkler irrigation, and cultivate in well-ventilated areas. Removing infected leaves and plant debris reduces inoculum density. Additionally, timely pruning should be performed before the disease spreads, and protective fungicide applications should be considered when necessary (Stuteville & Erwin, 1990).

2.2.3. Leaf Spot Disease of Alfalfa (*Pseudopeziza medicaginis* (Lib.) Sacc.)

Symptoms and Damage: The ailment typically initiates on the foliage as small, round, dark brown to black lesions. The spots often do not impact the adjacent leaf tissue and, with time, evolve into slightly elevated apothecia (fruit bodies) that transition from dark brown to black at the centre. The peripheries of the spots may be either smooth or serrated. The affliction typically initiates on the leaves and subsequently advances to the stems and petioles. Chlorosis, desiccation, and premature abscission are evident on affected leaves. Under cool, humid conditions (about 20 °C), spores maturing in the apothecia are released into the atmosphere, resulting in new infections. The disease does not eradicate the plant but induces premature leaf abscission, resulting in an approximate 40% drop in dry matter output and a notable decline in feed quality (crude protein and digestibility). Moreover, the elevation of oestrogenic chemicals in infected plants may negatively impact reproductive efficacy in dairy calves (Morgan & Parbery, 1980; Nutter Jr et al., 2002; Gui et al., 2016; Li et al., 2018).

Management: It is advisable to select resistant varieties, avoid spray irrigation, and cultivate in well-ventilated areas to manage the disease. Eliminating diseased foliage and plant detritus from the field diminishes inoculum density. Harvesting should not be delayed, as the disease intensifies in older plants. Additionally, the use of protective or systemic fungicides on seedlings is advised. While the disease does not immediately cause lethal effects on the plant, it can lead to significant reductions in leaf abscission, forage quality, and yield, necessitating routine field assessments and appropriate agronomic practices (Stuteville & Erwin, 1990; Li et al., 2018).

2.2.4. Downy Mildew on Alfalfa (*Peronospora trifoliorum* d By. *P. viciae* (Berk.):

Symptoms and Damage: Mildew disease in alfalfa is common, especially in tranquil, humid environments, and can cause considerable damage during its early stages. Infection commences with a pale green discolouration on juvenile leaves. Gradually, the leaf edges curl slightly, and a greyish-white, mould-like mycelial layer develops on the underside. As the illness advances, the leaves become entirely yellow, the plants deteriorate, and in most instances, blossoming fails to occur. Chilly, humid conditions, particularly throughout spring and autumn, exacerbate the severity of the illness. The pathogen can persist for years via oospores generated in decayed plant tissues and enduring mycelia in the plant's crown buds (Onar, 2005; Stuteville & Erwin, 1990).

Management: Infected plants must be eradicated from the field and disposed of to manage the illness. Selecting resilient alfalfa cultivars and utilising clean, certified seeds mitigates the danger of illness. Moreover, in regions where the illness reoccurs annually, effective crop rotation must be instituted, and adequate drainage should be maintained to avert excessive moisture buildup. Prompt monitoring and action, along with cultural practices, substantially reduce the proliferation of mildew (Alptekin and Erol, 2004; Stuteville & Erwin, 1990).

2.2.5. Phoma Leaf Spot on Alfalfa (*Phoma medicaginis* Malbr. & Roum. var. *P. medicaginis* Boerama)

Symptoms and Damage: The infection begins as small dots on the leaves, which progressively enlarge and develop into slightly depressed, light-brown regions. Infected leaves exhibit yellowing, desiccation, and typically curl prior to abscission.

Lesions on the stem and petiole coalesce to create dark, uneven patches. Under humid conditions, seed capsules undergo discolouration, shrinkage, and deformation. The infection disseminates through water, wind, and insects. Dew and precipitation are essential for spore dissemination from pycnidia and the initiation of new infections (Stuteville and Erwin, 1990).

Management: The most effective approach to managing the condition is reducing moisture levels and improving air circulation within the field. Infected plant detritus must be eliminated, irrigation should be regulated, and sprinkler systems should be eschewed. The use of resistant types, timely cultivation, and effective field sanitation significantly curtails the dissemination of the illness. In extreme instances, chemical management may be implemented utilizing formulations that contain sulfur or suitable fungicides (Umar et al., 2022).

2.2.6. Anthracnose in Alfalfa *(Colletotrichum trifolii* Bain*)*

Symptoms and Damage: The disease often emerges in late spring or early summer, presenting as pale, diamond-shaped lesions on alfalfa stems and petioles. The 'shepherd's crook' curvature is characteristic of diseased stems. Dark formations (acervulus) that produce spores emerge at the centre of the lesions, and these spores induce new infections. As the ailment advances, the stem tissue becomes brown, the higher portions deteriorate, and the plant's vitality diminishes. Under optimal warm, humid conditions, the pathogen may disseminate to the root and crown tissues, resulting in the plant's total demise (Johnson, 1968).

Management: The principal strategy for disease prevention is the cultivation of resistant alfalfa cultivars. To prevent the spread of contaminated plant debris and spores, harvesting equipment must be maintained clean and disinfected with a 10% chlorine solution, particularly when transitioning from severely infected fields to uninfected regions. Furthermore, eliminating infected material post-harvest and maintaining field conditions that promote adequate air circulation helps mitigate the spread of the illness.

2.2.7. Alfalfa Rust *(Uromyces striatus* Schroet. *var medicaginis)*

Symptoms and Damage: The disease is typically detected in the summer and autumn seasons. Minute, reddish-brown rust pustules (uredosporangia) develop on alfalfa leaves, petioles, and stems. These structures penetrate the leaf epidermis and, in severe infections, induce premature leaf shrivelling and abscission. The disease may also advance to the stems during phases with extended internodes (Jordan).

Management: Host plants that harbour the disease throughout winter (e.g., *Euphorbia cyparissias*) must be eradicated. Employing resistant alfalfa cultivars and removing contaminated plant detritus from the field helps mitigate disease transmission.

2.2.8. Alfalfa Black Spot Disease *(Macrosporium sarciniforme)*

Symptoms and Damage: The illness starts with small black spots on the leaves, which then dry up all leaf and branch tissues. In places with many plants and high humidity, the illness is usually worse.

Management: Don't plant too closely together in the field, and do not do anything that makes the air too humid, including watering too much or not allowing enough air to flow through. These steps greatly slow the transmission of the disease (Stuteville and Erwin, 1990).

3. ALFALFA BACTERIAL DISEASES

3.1. Bacterial Leaf Spot (*Xanthomonas campestris* pv. *alfalfa*)

***Symptoms and Damage*:** Prevalent in temperate areas, this disease induces the formation of tiny, angular, water-soaked lesions on foliage. These lesions, typically originating on the abaxial leaf surface, coalesce and enlarge, with their centres becoming yellow and translucent. In extreme instances, foliar abscission transpires. Moist, greasy lesions may develop on the stem and extend along the internodes.

Management: Choosing resistant cultivars and planting in spring within temperate zones mitigates seedling mortality (Arsenijevic and Klement, 1969).

3.2. Bacterial Wilt Disease (*Clavibacter michiganensis* subsp. *insidiosus*)

Symptoms and Damage: The disease occurs under arid, elevated-temperature conditions, characterised by wilting, stunting, and upward curling of leaf margins. In advanced stages, the stem becomes robust, the plant assumes a shrub-like morphology, and pale necrosis manifests on diminutive leaves. This condition resembles Verticillium wilt, although the stunting is characteristic of this particular disease (Umar et al., 2022).

Management: It is advisable to utilise resistant cultivars. Equipment must be kept clean throughout harvesting, and younger plants should be harvested before older ones. Plants must not be harvested when moist.

3.3. Bacterial Stem Blight (*Pseudomonas syringae* pv. *syringae* van Hall.)

Symptoms and Damage: In this disease, which occurs in cold and high-altitude regions, yellowish-green, watery spots form on the stem, extending along the internodes and weakening the stem. Infected stems exhibit brittleness, reduced length, and susceptibility to fracture. Yellowing and wilting are evident along the petiole. It typically manifests after late-spring frosts.

Management: In the absence of resistant varieties, it is imperative to select frost-tolerant varieties. Pruning should be conducted promptly once the risk of frost has subsided, and any contaminated plant waste must be eliminated from the field (Riker et al., 1935).

3.4. Shoot Blight (*Pseudomonas medicaginis*)

Symptoms and Damage**:** The disease is typically transmitted via bacteria infiltrating through insect-induced damage or mechanical injuries. Infected shoots initially exhibit yellowing; thereafter, they blacken, bend, and desiccate. It is typically observed after winter and throughout the initial growing phase.

Management: Pest management must be implemented to mitigate plant damage (Dye et al., 1980).

3.5. Root Rot (*Aplanobacter insidiosum*)

Symptoms and Damage**:** The condition predominantly manifests in years characterized by frost damage. The bacterium infiltrates via lesions in the root collar, resulting in brown proliferations within the tissue. As time progresses, the root decays, plant growth ceases, and localized wilting manifests.

Management: Affected regions must be tilled and eradicated. Alfalfa should not be planted consecutively in the exact location, and resistant types should be prioritized in future plantings (Gabriel et al., 1986).

4. VIRUS DISEASES SEEN IN ALFALFA

4.1. Alfalfa mosaic alfamovirus (AMV)

***Symptoms and Damage*:** The seed-borne virus can induce a range of symptoms in plants. Infected leaves display uneven discolouration varying from pale yellow to cream. Certain leaves exhibit wrinkling, distortion, pale green-yellow chlorotic patches, streaks, or ring-shaped manifestations. In severe infections, the plant exhibits overall chlorosis and experiences deterioration.

***Management*:** To manage the disease, use resistant cultivars, remove diseased plant debris, and eliminate host weeds. Infected plants in greenhouses or fields should be promptly removed and disposed of.

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MECHANISM ACTION OF MICROBIAL FERTILIZERS

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1. INTRODUCTION

Throughout human history, agriculture has been one of the most important economic and social activities that laid the foundations of civilization. Agriculture is of strategic importance not only in terms of food production but also in terms of employment, energy production, the preservation of biological diversity, and ensuring environmental sustainability (Doğan, 2024). Today, with the rapid growth of the world's population, the pressure on food production is also increasing. According to data from the Food and Agriculture Organization of the United Nations (FAO), the world's population is expected to reach approximately 9.7 billion by 2050 (FAO, 2023). This increase will strain the capacity of existing food production systems and necessitate agriculture to produce more with fewer resources. However, despite the growing population, it is not possible to expand arable farmland. Urban sprawl, industrialization, soil erosion, salinization, and land degradation due to climate change are rapidly reducing the amount of arable land per capita. This situation necessitates increasing the yield

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per unit area; consequently, production pressure is increasing with the intensive use of chemical fertilizers and pesticides in conventional farming methods.

The Green Revolution of the second half of the 20th century promoted the use of chemical fertilizers and pesticides, leading to significant short-term increases in crop yields. However, in the long term, these practices have led to serious environmental problems such as soil degradation, loss of biodiversity, ecological disruption, nitrate leaching, water pollution, nutrient imbalances, and increased atmospheric greenhouse gas emissions. Due to the continuous use of chemical fertilizers, organic matter in the soil has decreased, microbial diversity has declined, and ecosystem cycles have been damaged. In particular, the excessive use of nitrogen fertilizers causes contamination of groundwater through nitrate leaching, while the intensity of phosphate fertilizers increases the risk of eutrophication (Rathod et al., 2024).

At this point, sustainable and environmentally friendly approaches to agricultural production are coming to the fore. Today, microbial-based biofertilizers (microbial fertilizers) are at the center of strategies that aim to reduce agricultural inputs while maintaining productivity. Microbial fertilizers (biofertilizers) stand out as sustainable alternatives that make nutrients more accessible through “biological” pathways and increase stress tolerance by managing plant-microorganism-soil interactions. This approach has direct effects such as the biological fixation of atmospheric nitrogen, the dissolution and mobilization of insoluble phosphate and micronutrients, the production of plant growth hormones (IAA, GA, cytokinin), and the improvement of root structure (Rhizobium, Azotobacter, Bacillus, Pseudomonas, Trichoderma, mycorrhizal fungi, etc.). Systemic resistance induced in the root zone (ISR), pathogen suppression, siderophore-mediated iron acquisition, and the promotion of a healthy microbial community (microbiome) (Liu et al., 2022). Thus, they contribute to restoring natural cycles while reducing the negative environmental impacts of chemical fertilizers and pesticides. The strategic importance of microbial fertilizers is increasing, both in terms of efficient management of nutrient cycles (especially N and P) and climate-resilient agricultural practices. Regarding phosphorus: The limited global P resources, mostly found in insoluble forms, have made the availability of P to plants through organic acids and phosphatase enzymes produced by phosphate-solubilizing bacteria (PSB) critical (Rodríguez and Fraga, 1999; Pan and Cai, 2023). Similarly, arbuscular mycorrhizal fungi (AMF) functionally expand the root surface, accelerating nutrient uptake, particularly phosphorus, and improving water use efficiency and photosynthetic performance (Bhupenchandra et al., 2024). In the last 10-15 years, consortium-based biofertilizers (Rhizobium + PSB + AMF) have come to the fore. These consortia simultaneously increase BNF (biological nitrogen fixation) capacity and P mobilization while also triggering defense/accessory mechanisms such as ISR and siderophore production, supporting plant growth even under stress conditions. Thus, microbial fertilizer becomes not only a "nutrient" but also a tool for health and resilience management (Pieterse et al., 2014; Backer et al., 2018).

The importance of microbial fertilizers is significant not only in terms of environmental sustainability but also in terms of economic sustainability. Particularly in low-income agricultural regions, the high cost of accessing chemical fertilizers makes the use of biofertilizers a low-cost alternative for farmers (Richa, 2023). However, the effectiveness of biofertilizers is directly related to the correct strain selection, suitable carrier material, environmental conditions, and proper application techniques. Considering agriculture's strategic role in human nutrition, it seems inevitable to develop microbial fertilizer-based production systems that will reduce dependence on chemical fertilizers, preserve the natural balance, maintain soil vitality, and support long-term productivity. These approaches are emerging as a fundamental solution area in 21st-century agriculture for ensuring both food security and ecological integrity. This section covers the mechanisms of action and applications of microbial fertilizers, which offer promising alternatives to chemical fertilizers that disrupt the natural balance, as well as future target expectations.

2. MECHANISM ACTION OF MICROBIAL FERTILIZERS

The effect of microbial fertilizers on plant growth depends on the biochemical activities produced by microorganisms in the rhizosphere. These microorganisms enhance plant nutrition through direct mechanisms such as nutrient mobilization, nitrogen fixation, and the synthesis of plant growth regulators, while also supporting plant health through indirect mechanisms such as pathogen suppression, induced systemic resistance (ISR), and microbial competition These interactions establish a sustainable balance within the plant-microorganism-soil triad, increasing productivity and resistance to environmental stress factors (Pieterse et al., 2014). The effects of microbial fertilizers are divided into two main groups: direct (nutrient uptake and growth stimulation) and indirect (defense and microbiota regulation) **(Figure 1)** (Wang et al., 2024).

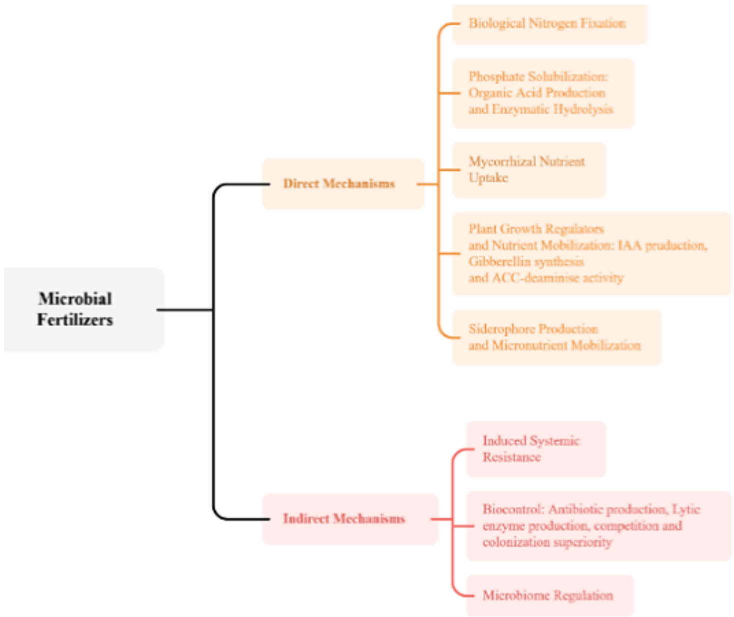

Figure 1. Mechanisms of Action Microbial Fertilizers

2.1. Direct Mechanisms

The physiological, biochemical, and molecular interactions between plants and microorganisms are fundamentally based on the direct effects of microbial fertilizers on plant growth. These interactions facilitate nutrient uptake, enhance root system development, and stimulate plant metabolism through growth-regulating hormones. These mechanisms are explained below in subheadings.

2.1.1. Biological Nitrogen Fixation (BNF)

Nitrogen is one of the essential macronutrients for plants and plays a critical role in chlorophyll synthesis, amino acid, and protein formation. However, N_2 gas, which constitutes 78% of the atmosphere, cannot be directly utilized by plants. Biological nitrogen fixation (BNF) is the process by which this gas is converted into ammonia (NH_3) by microorganisms. This mechanism occurs in two different ways:

Symbiotic fixation: Bacteria such as Rhizobium, Bradyrhizobium, Sinorhizobium, and Ensifer form symbiotic relationships with leguminous plants and fix nitrogen in root nodules. The symbiosis between *Medicago sativa* (clover) and *Sinorhizobium meliloti* provides high levels of nodule formation and N_2 fixation (Provorov et al., 2023).

Free-living or associative nitrogen fixation: Bacteria such as Azotobacter, Azospirillum, Herbaspirillum, and Beijerinckia fix atmospheric nitrogen by living freely on the root surface or in the rhizosphere. *Azospirillum brasilense* increases nitrogen content and green biomass weight in corn and wheat (Flora et al., 2021).

Nitrogen fixation is catalyzed by the nitrogenase complex; this enzyme is oxygen-sensitive and requires ATP consumption. Therefore, microorganisms produce carrier proteins such as leghaemoglobin to reduce the effect of oxygen. The agricultural importance of nitrogen fixation is considerable; legume-rhizobium systems contribute approximately 200 million tons of atmospheric nitrogen to agricultural systems annually. Symbiotic rhizobia (Rhizobium/Ensifer spp.) reduce N_2 to ammonia in legume root nodules; free-living diazotrophs (Azotobacter, Herbaspirillum) can also contribute nitrogen. This process reduces the need for chemical N fertilizers and supports protein accumulation. BNF yield is closely related to strain-host matching, soil pH, oxygen/carbon flux, and trace elements (Glick, 2012).

2.1.2. Phosphate Solubilization and Organic P Mineralization

Phosphorus (P) is an essential macronutrient involved in many vital processes in plants, such as energy transfer, photosynthesis, nucleic acid synthesis, and cell membrane formation. However, most phosphorus in the soil is in forms that cannot be directly taken up by plants. It is usually bound in the soil as insoluble compounds such as calcium phosphate ($Ca_3(PO_4)_2$), iron phosphate ($FePO_4$), and aluminum phosphate ($AlPO_4$). The provision of orthophosphate ions ($H_2PO_4^-$, HPO_4^{2-}) available to plants is carried out by phosphate-solubilizing microorganisms (PSM) (Rodríguez and Fraga, 1999).

These microorganisms are effective in two main ways:

Organic acid production: PSMs (*Bacillus megaterium*, *Pseudomonas fluorescens*, *Burkholderia cepacia*) mobilize insoluble phosphates by secreting organic acids such as gluconic, citric, lactic, succinic, oxalic, and malic acids. These acids lower soil pH, releasing calcium-bound phosphates (Sharma et al., 2013). In addition, siderophores produced by these microorganisms increase the solubility of microelements such as iron and zinc, indirectly contributing to plant nutrition.

Enzymatic hydrolysis: Microorganisms that produce phosphatase enzymes, such as *Aspergillus niger*, *Bacillus megaterium*, and *Penicillium* spp., convert organic P compounds into inorganic forms. An increase of up to 30% in phosphorus uptake was observed in corn plants inoculated with *Bacillus polymyxa*. The effect of PSMs is particularly pronounced in low-phosphorus or calcareous soils, reducing the need for chemical phosphate fertilizers (Sharma et al., 2013). This mechanism is especially effective in soils where organic fertilizers are applied or where microbial activity is high.

PSBs solubilize Ca-, Al-, and Fe-bound phosphates through organic acids (gluconic, citric), phosphatase enzymes, and sometimes proton release, making them available to the plant. The mechanism involves periplasmic acidification and solubilization via pqq-dependent glucose dehydrogenase (gcd). PSB applications in field and pot trials have significantly increased phosphorus uptake and biomass (Rodríguez and Fraga, 1999; Sharma et al., 2013; Pan and Cai., 2023).

2.1.3. Expansion of Mycorrhizal Nutrient Uptake and Root Functions

Mycorrhizal fungi are microorganisms that form a mutualistic relationship with plant roots, thereby facilitating and expanding the plant's access to nutrients. Mycorrhizal symbiotic relationships are divided into two main groups: ectomycorrhizae and arbuscular mycorrhizae (AMF). Ectomycorrhizae are typically found in forest ecosystems/habitats, symbiotically associated with woody tree species such as pine and oak. In contrast, the most common type of symbiosis seen in agricultural systems is arbuscular mycorrhizal fungi (AMF), which belong to the Glomeromycota phylum and enter root cortex cells to form structures called “arbuscules.” These hyphal structures increase the root surface area, facilitating the transport of nutrients that are low in mobility, such as phosphorus, zinc, and copper. A 25-40% increase in phosphorus uptake has been observed in wheat plants infected with *Glomus intraradices*. In addition, mycorrhizal colonization increases the plant's resistance to water stress by regulating the root-air-water balance. Mycorrhizal symbiosis is also effective at the hormonal level, optimizing the balance of cytokinin and abscisic acid (ABA) in the root, thereby improving root morphology. In legumes, the combined use of mycorrhizal fungi and Rhizobium (dual inoculation) creates a synergistic effect that increases both nitrogen fixation and phosphorus use efficiency (Brundrett and Tedersoo, 2018).

AMF hyphae enable the uptake of low-diffusion nutrients, primarily phosphorus, from areas distant from the roots; Pi flow is accelerated through H^+-ATPase activity in the root membrane and Pi transporters between the fungus and plant. AMF colonization also increases water use efficiency and photosynthetic performance (Bhupenchandra et al., 2024).

2.1.4. Plant Growth Regulators and Nutrient Mobilization

Many bacterial and fungal species found in microbial fertilizers have the ability to produce biochemical compounds that support plant growth. These microorganisms not only ensure more efficient utilization of nutrient elements by plants but also directly influence the plant's physiological processes by synthesizing phytohormones, known as plant growth regulators. Phytohormone production and nutrient mobilization form the basis of the “biostimulant” effect of microbial fertilizers. Plant growth-promoting rhizobacteria (PGPR) can synthesize various phytohormones that affect root and shoot development in plants. Among these, the most important are indole acetic acid (IAA), gibberellins (GA), cytokinins, abscisic acid (ABA), and ethylene regulatory compounds.

- ***IAA production:*** IAA, synthesized via the tryptophan pathway, stimulates root cell division and elongation, increasing the plant's nutrient uptake surface. In wheat roots treated with Azospirillum brasilense, root volume and root hair density increased by 35% (Wang et al., 2022).
- ***Gibberellin synthesis:*** Gibberellins produced by Bacillus subtilis and Pseudomonas putida promote shoot elongation and flowering in plants (Bhattacharyya and Jha, 2012).
- ***Cytokinin production:*** Microbial cytokinins promote cell division and increase chlorophyll synthesis, thereby enhancing photosynthetic capacity (Glick, 2012).

- ***ACC-deaminase activity:*** Some PGPR species (Enterobacter cloacae, Pseudomonas putida) limit stress-induced ethylene production in plants by breaking down ACC, the precursor of ethylene; this supports growth, particularly under salt and drought stress. These biosynthetic activities provide both economic and ecological advantages by offering a natural alternative to chemical growth regulators.

Many PGPRs promote root branching and root hair formation by synthesizing IAA, gibberellin, and cytokinin, which increases nutrient and water uptake. At the same time, siderophore production chelates Fe+3, facilitating iron uptake by the plant; this effect is particularly pronounced in calcareous/alkaline soils (Glick, 2012; Backer et al., 2018; Deb and Tatung, 2024).

2.1.5. Siderophore Production and Micronutrient Mobilization

Iron (Fe) is one of the microelements that is vital for plants. It plays a role in many metabolic processes such as photosynthesis, respiration, chlorophyll synthesis, and enzymatic reactions. However, the bioavailability of iron in soil solution is quite low. Iron (Fe^{3+}) solubility is particularly low under alkaline conditions. In alkaline or calcareous soils, iron is usually present in the insoluble Fe^{3+} form and cannot be directly absorbed by plants. Microorganisms synthesize low molecular weight organic compounds called siderophores to solve this problem. Siderophores complex Fe^{3+} ions, making them easier for plants to absorb. Siderophores render Fe^{3+} ions water-soluble through high-affinity ligand interactions. Microorganisms transport this complex to the cell surface to assimilate iron and also indirectly assist plants by increasing Fe^{3+} solubility in the rhizosphere. Pyoverdin, synthesized by Pseudomonas fluorescens, provides iron to the plant while also acting as a biocontrol agent by blocking pathogen microorganisms' access to Fe. This dual effect improves plant nutrition while also reducing disease pressure.

Similarly, siderophore synthesis may also contribute to the mobilization of trace elements such as zinc (Zn) and manganese (Mn) (Tirry et al., 2018). Siderophore-producing bacteria are frequently used in microbial fertilizer formulations, particularly in calcareous soils showing nutrient deficiencies. Recent studies have shown that siderophore production has an ecological function in both nutrient acquisition and maintaining the balance of the rhizosphere microbiota. Siderophore-producing bacteria gain a competitive advantage in the rhizosphere and colonize the surface of plant roots more efficiently. This facilitates and supports the continuity of the symbiotic relationship between plants and microorganisms and increases the long-term effectiveness of microbial fertilizers. (Deb and Tatung, 2024).

2.1.6. Organic Matter Transformation and Enzymatic Activity

The sustainability of soil fertility largely depends on the decomposition rate of organic matter present in the soil and the degree of enzymatic activity. Organic matter is formed by the accumulation of plant and microbial waste and is a fundamental component that regulates both the physical and chemical balance in the soil ecosystem. Microbial fertilizers accelerate the mineralization of organic matter, allowing nutrients to enter the cycle. In this process, microorganisms produce a series of enzymes that convert complex organic molecules into simple inorganic forms. This increases the bioavailability of essential elements such as nitrogen (N), phosphorus (P), sulfur (S), and carbon (C), which are necessary for plant growth. Many microbial fertilizers accelerate the nutrient cycle by secreting enzymes (cellulase, protease, phosphatase, hydrolase, oxidase, transferase, etc.) that break down organic compounds in the soil. Proteases produced by Bacillus licheniformis convert organic nitrogen into ammonia, making it available for plant uptake. This process maintains the carbon/nitrogen balance in the soil. Additionally, the decomposition of microbial cell wall components (glucan, chitin, lipopolysaccharide) contributes to the recycling of organic carbon in the soil. *Bacillus*, *Pseudomonas*, *Trichoderma*, and *Aspergillus* species have high enzyme activity. The cellulase, chitinase, and protease enzymes produced by *Trichoderma harzianum* both accelerate organic matter conversion and provide a biocontrol effect by breaking down the cell walls of pathogenic fungi. These mechanisms support humus formation while increasing soil fertility in the long term. The phytase enzyme synthesized by *Bacillus subtilis* facilitates phosphorus uptake by plants by releasing inorganic phosphate from organic phosphorus compounds. (Bhattacharyya and Jha, 2012; Choudhary et al., 2022; Tian et al., 2024).

The conversion of organic matter and enzymatic activity are among the most important roles of microbial fertilizers in terms of productivity and quality in agricultural production. These biochemical mechanisms accelerate the cycle of nutrients in the soil, primarily nitrogen. In addition, microbial diversity increases and the need for chemical fertilizers decreases. In line with this objective, an environmentally friendly production system compatible with sustainable agriculture goals can be developed.

2.2. Indirect Mechanisms

The effect of microbial fertilizers on plants is not limited to direct nutrient supply and growth regulator synthesis. These microorganisms also protect and improve plant health through indirect mechanisms, increase stress tolerance, and contribute to strengthening the rhizosphere ecosystem by maintaining its balance. The indirect effects of microbial fertilizers that support plant development occur not so much through processes such as direct nutrient supply or hormone production, but rather through the reorganization of rhizosphere ecology, the stimulation of plant resilience/defense mechanisms, the suppression of soil pathogens (biocontrol), and the maintenance of microbial community balance. These mechanisms generally stem from complex biochemical and ecological interactions between the plant and microbial colony populations. They contribute to the plant's ability to continue growing under stress conditions, survive, and develop a physiological structure that is resistant to environmental abiotic/biotic factors.

Indirect mechanisms encompass multifaceted, complex processes such as induced systemic resistance (ISR), microbial biocontrol, competition, antibiotic production, volatile organic compound (VOC) synthesis, siderophore synthesis, and regulation of the rhizosphere microbiota (Pieterse et al., 2014; Backer et al., 2018). The indirect effects of microbial fertilizers are mostly based on enhancing the plant's own defense system through “priming” (pre-stimulation). Plants block most microbes at the front lines with a non-host resistance strategy. This includes physical barriers such as waxy cuticles, rigid cell walls, and antimicrobial secondary metabolites. When pathogens successfully overcome these barriers, they encounter an effective plant immune system that halts the progression of microbial colonization. In this case, the plant prepares itself against potential pathogens or stress factors, accelerating the activation of defense genes while also becoming dynamically active. Thus, defense responses are regulated more effectively in terms of energy use. Indirect mechanisms also create long-term ecological stability within the plant-microorganism-soil relationship system. The dominance of beneficial microbial populations provides biocontrol in the root zone, a balanced nutrient element cycle, and metabolic balance in stress factors (Backer ve ark., 2018).

2.2.1. Induced Systemic Resistance (ISR) and Defense Priming

Plants possess a sophisticated, complex defense mechanism against pathogen attacks and environmental stress factors. This mechanism is not limited to responses activated by direct contact; it also encompasses indirect defense mechanisms such as induced systemic resistance (ISR) produced by beneficial microorganisms. ISR is based on the principle of defense priming, which means "preparing" or "pre-activating" the plant's defense genes prior to pathogen attack. ISR is the mechanism by which the plant's immune system is brought into a "ready state" before exposure to abiotic or biotic stress factors. ISR is usually initiated by plant growth-promoting rhizobacteria (PGPR) or mycorrhizal fungi and begins with the activation of jasmonate (JA) and ethylene (ET) signaling pathways within plant tissues. *Bacillus subtilis*, *Pseudomonas fluorescens*, *Trichoderma harzianum*, and *Rhizobium* spp. stand out for this feature. These microorganisms interact directly with the plant to activate its systemic defense pathways by producing signaling molecules. This enables the plant to exhibit reactions such as cell wall strengthening, callose accumulation, phenolic chemical synthesis, and expression of defense genes (PDF1.2, PR-1, LOX2) without being exposed to pathogen attack. Cucumber plants treated with *Pseudomonas fluorescens* have been observed to exhibit enhanced resistance against fungal pathogens, including those affecting above-ground tissues; Similarly, the use of *Bacillus subtilis* has been reported to confer resistance to Fusarium oxysporum in tomato plants via ISR (Pieterse et al., 2014; Kamle et al., 2020).

An important feature of the ISR mechanism is that it is an energy-efficient defense system; because the plant synthesizes costly defense metabolites in response to biotic or abiotic stress constraints. This situation is called "defense priming" and balances plant development with defense. In addition, several microbial metabolites-2,4-diacetylphloroglucinol (DAPG), pyocyanin, surfactin, lipopeptides-contribute to ISR by triggering defense responses in plants. These chemical metabolites are generally found at minimal levels in the root region but create a systemic defense response in distant tissues. Among indirect mechanisms, ISR and defense priming are the most complex and effective in microbial fertilizers. These mechanisms enable plants to manage their defense systems more efficiently and effectively against environmental factors. ISR-based microbial fertilizer applications are important for biological resilience and ecological balance in sustainable agriculture (Serteyn et al., 2020).

2.2.2. Biocontrol: Antibiotics, Lytic Enzymes, and Competition

The plant rhizosphere region is a dynamic ecosystem structure where beneficial and harmful microorganisms compete for nutrients, water, and space. In this ecosystem, beneficial bacteria and fungi found in microbial fertilizers inhibit pathogenic microorganisms and play a role in biological control through their antagonistic properties. Biocontrol is an environmentally friendly protection strategy that has emerged as an alternative to the harmful effects of chemical pesticides on the environment. Biological control/biological warfare is a biological process in which beneficial microorganisms directly suppress pathogens to protect plant health. This mechanism is one of the most powerful indirect benefits of microbial fertilizers to plants and works through three basic systems:

Antibiotic production: Antibiotic synthesis is the most effective biocontrol method used by beneficial microorganisms. These microorganisms synthesize secondary metabolites that stop the growth of pathogens or kill them by disrupting their cell membranes. *Pseudomonas fluorescens, Bacillus subtilis,* Streptomyces, and *Trichoderma harzianum* species secrete effective antibiotics (2,4-DAPG, pyrrolnitrin, iturin, fengycin, surfactin) against pathogenic fungi. Iturin, produced by *Bacillus subtilis,* stops the growth of *Rhizoctonia solani* by breaking down its cell wall (Raaijmakers et al., 2002).

Lytic enzyme production: Some microorganisms directly inactivate pathogens by breaking down the structural polymers in their cell walls. Microorganisms such as *Trichoderma harzianum* and *Pseudomonas cepacia* break down fungal cell walls by producing enzymes such as chitinase, β-1,3-glucanase, cellulase, and protease (Vinale et al., 2008).

Competition and colonization superiority: Beneficial bacteria prevent the colonization of pathogens in the rhizosphere by competing for nutrients (Fe^{3+}, organic carbon) and niches. This occurs particularly through the siderophore production of *Pseudomonas fluorescens*. Another dimension of biocontrol is the quorum sensing and quorum quenching mechanisms. Some beneficial bacteria disrupt the infection signaling chain by breaking down communication signals (AHL molecules) dependent on pathogen cell density. Bacillus cereus strains have reduced bacterial wilt disease by disrupting the quorum sensing mechanism of *Ralstonia solanacearum* (Sing et al., 2022).

2.2.3. Microbiome Regulation and Soil Functionality

Soil is not only a physical growth medium but also a complex biological ecosystem that plays a decisive role in plant health, nutrition, and resilience. The most important component of this ecosystem is the soil microbiome, consisting of billions of microorganisms. Plants shape the surrounding microbial community through exudates secreted from their roots. Microbial fertilizers positively regulate this community, establishing balance in the plant-microorganism-soil triangle. Biofertilizer applications increase microbial diversity in the rhizosphere and "increase the proportion of beneficial bacteria while suppressing pathogenic populations." This strengthens the functional resilience of the microbial ecosystem and allows the plant to maintain a healthy root system even under stressful conditions. With the application of *Bacillus amyloliquefaciens*, the proportion of beneficial species such as Pseudomonas and Arthrobacter increased in the tomato rhizosphere, while the pathogenic Ralstonia decreased.

Additionally, AMF (*Glomus* spp.) contribute to organic matter stabilization by supporting the carbon cycle in the soil. This increase in microbial diversity in the rhizosphere both elevates soil enzyme activities (dehydrogenase, phosphatase) and permanently increases the bioavailability of nutrients. The microbiome regulation capacity of microbial fertilizers has great potential for sustainable agriculture. Thanks to these applications, microbial diversity in the soil ecosystem increases, functional roles are strengthened, and ecosystem resilience is maintained in the long term. The effective use of microbial fertilizers sustainably supports not only plant nutrition but also soil health, the carbon cycle, and biological balance (Sharma et al., 2013; Mahanty et al., 2017; Wu et al., 2025).

3. CONCLUSION AND FUTURE PERSPECTIVE

Microbial fertilizers play a role as strategic tools that serve as an alternative to chemical fertilizers and form the biotechnological basis of sustainable agriculture. A better understanding of plant-microorganism interactions has enabled these biofertilizers to perform various complex functions related to nutrient management, stress tolerance, soil health, and environmental sustainability in modern agricultural systems. Microbial fertilizers are innovative biotechnological solutions that strike a balance between sustainability, ecological protection, and economic efficiency in agricultural production. They hold great potential in terms of reducing the environmental pressures caused by chemical fertilizers, preserving soil microbial diversity, and sustaining ecosystem services. However, for these technologies to be applied on a large scale, standardization of production and distribution processes, development of farmer education programs, and implementation of supportive regulations at the policy level are required. Microbial fertilizers are also expected to play an increasingly important role in climate change adaptation strategies. The contribution of these products will be particularly important in areas such as carbon sequestration, water efficiency, and the preservation of soil biological activity. In line with global food security and environmental sustainability goals, the development of multi-functional microbial fertilizers that are adaptable to all soil types and ecosystems and have high local adaptability is considered one of the most important scientific and technological milestones of 21st-century agriculture.

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TARLA BİTKİLERİ YETİŞTİRME VE ISLAHI

DEĞERLENDİRMELERİ

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