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Review Article

Microbial Biofilms: Emerging Drivers of Enhancing Nutrient Use Efficiency in Agroecosystems

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Abstract

Efficient nutrient management is essential for sustainable crop production while reducing the environmental hazard from excessive use of synthetic fertilizers. Microbial biofilms are a structured community of microorganisms embedded in extracellular polymeric substances, emerged as important regulators of nutrient dynamics in soil plant environment. In rhizosphere, biofilm forming microorganisms enhance microbial stability, metabolic cooperation, and close interactions with plant roots. Biofilm associated microbes play crucial roles in phosphorus solubilization, nitrogen transformations, micronutrient mobilization, and organic matter decomposition. Biofilms also facilitate key soil processes such as nutrient solubilization, mineralization, and retention, thereby improving nutrient acquisition through root and enhance nutrient use efficiency (NUE). In addition, biofilm formation enhances microbial resilience under biotic, abiotic stresses that promote sustainable crop production in different agroecosystem. This review synthesizes current knowledge on the formation and ecological functions of microbial biofilms in agricultural soils, with a focus on their role in regulating nutrient cycling and improving NUE. We also discuss emerging opportunities for harnessing biofilm-forming microbial consortia and biofertilizer technologies to enhance nutrient efficiency and promote more sustainable agricultural systems.

Introduction

Improving nutrient use efficiency (NUE) has become a major focus for sustainable agriculture as excessive fertilizer inputs have led to declining soil health, nutrient losses, and environmental pollution, energy losses and economic loss. Globally, crops typically utilize 30-50% of applied nitrogen (N) and an even smaller fraction of phosphorus (P) and micronutrients fertilizers, resulting in significant economic losses and environmental risks such as eutrophication and greenhouse gas emissions [1-3]. Enhancing biologically mediated nutrient cycling within soil plant systems is therefore essential to improve nutrient utilization while maintaining agricultural productivity and resilience against stresses.

Recent advances in soil microbiology highlight the critical role of the soil microbiome and rhizosphere interactions in regulating nutrient availability, plant uptake and resilience under Stresses [4,5]. Microbial communities in the rhizosphere influence nutrient transformations including nitrogen fixation, phosphorus solubilization, micronutrient mobilization, and organic matter decomposition. Among these microbial strategies, biofilm formation has emerged as a key ecological mechanism through which microorganisms organize into structured communities embedded in extracellular polymeric substances (EPS). Biofilms are structured communities of microorganisms embedded within a self-produced EPS matrix attached to biotic or abiotic surfaces. The EPS matrix, primarily composed of polysaccharides, proteins, lipids, and extracellular DNA, provides structural stability, protects microorganisms from environmental stress, and facilitates microbial communication and metabolic cooperation. They represent a dominant microbial lifestyle in natural ecosystems and play a significant role in nutrient cycling and utilization [6,7]. In agricultural systems, biofilms formed by bacteria, fungi, and cyanobacteria in the rhizosphere contribute to enhance microbial survival, metabolic cooperation, and stable colonization of plant roots, thereby facilitating efficient nutrient cycling in the rhizosphere [8,9]. Biofilms also contribute to the bioremediation of contaminated soils, as microbial communities embedded within EPS matrix can degrade environmental pollutants including polycyclic aromatic hydrocarbons PAHs, toluene, and pesticides more efficiently than planktonic cells while the matrix enhances microbial protection and metabolic activity under stressful conditions [10,11]. In addition, EPS produced by biofilm-forming microorganisms acts as a natural binding agent that stabilizes soil particles, and enhancing water retention and aeration, thereby supporting soil health and ecosystem functioning [12].

Several recent reviews have discussed the role of plant growth promoting rhizobacteria, soil microbiomes, and microbial nutrient cycling in agricultural soils [13]. However, the specific role of microbial biofilm architecture in regulating nutrient use efficiency within agroecosystems has not been comprehensively synthesized. Most studies focused on individual microbial processes or biofertilizer applications, while the integrative role of biofilm-mediated microbial interactions in improving NUE remains poorly understood. We hypothesize that microbial biofilms act as key ecological drivers that enhance nutrient retention, transformation, and plant availability, ultimately improving NUE in agroecosystems. This review synthesizes recent advances in biofilm formation, rhizosphere microbial interactions, and nutrient cycling processes, and highlights opportunities to harness biofilm-forming microbial consortia for improving nutrient efficiency and promoting sustainable agricultural systems.

Biofilm Formation and Structure

Biofilm formation is a dynamic and highly regulated process involving microbial communication, surface attachment, and production of extracellular polymeric substances. The development of biofilms typically proceeds through several stages (i) initial reversible attachment, (ii) irreversible attachment and formation of a microbial monolayer, (iii) microcolony formation, (iii) biofilm maturation and three-dimensional architecture development, and (iv) dispersion of cells from the mature biofilm (Figure 1).

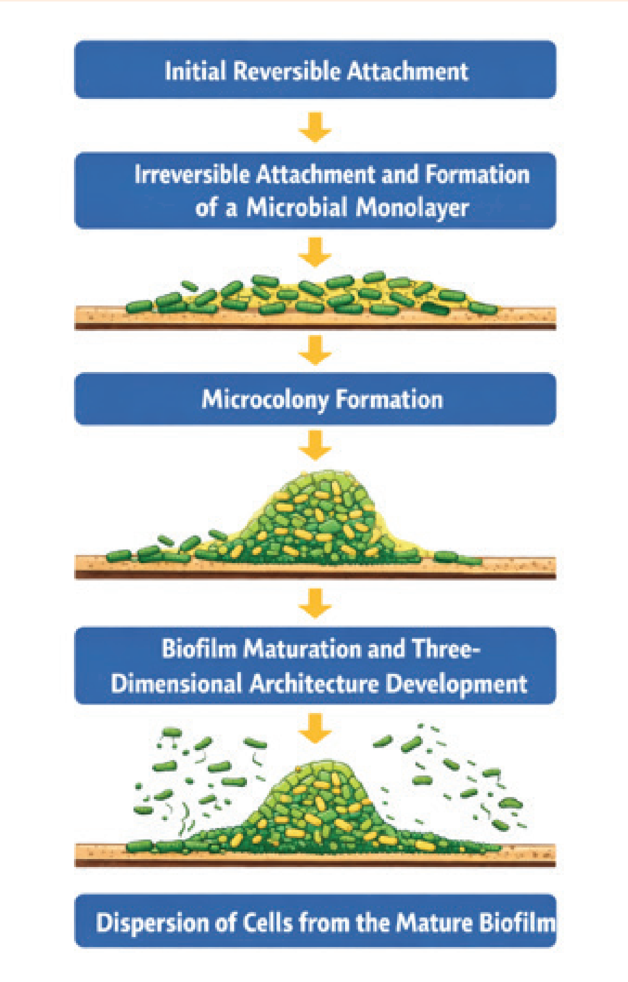

Figure 1: Biofilm formation mechanism showing stages of initial attachment, microcolony formation, biofilm maturation, and dispersion.

During the initial stage of biofilm formation, planktonic microbial cells attach to surfaces through weak physicochemical interactions such as van der Waals forces and hydrophobic interactions [14,15]. This reversible attachment gradually becomes irreversible through cellular appendages such as pili and flagella; for instance, type IV pili in Pseudomonas aeruginosa play a crucial role in stable surface colonization [15,16]. Following attachment, microorganisms produce extracellular polymeric substances (EPS), which may constitute up to 80% of the biofilm dry mass and form a protective matrix composed mainly of polysaccharides, proteins, lipids, and extracellular DNA [17]. This matrix provides structural stability, regulates nutrient diffusion, and protects microbial communities from environmental stresses while enabling close spatial interactions that facilitate metabolic cooperation and syntrophic relationships. Biofilm formation is further regulated by quorum sensing (QS), a cell-to-cell communication mechanism in which microbes coordinate gene expression through diffusible signaling molecules known as autoinducers. When microbial population density reaches a threshold, these signals activate genes responsible for EPS production, adhesion, motility, and secondary metabolite synthesis [7]. Consequently, biofilm microenvironments develop gradients of oxygen, pH, and nutrients, supporting diverse microbial metabolic activities and enhancing nutrient transformations within the system.

Biofilm and soil health

EPS are key structural and functional components of microbial biofilms, play a vital role in maintaining soil health and microbial activity. The EPS matrix, primarily composed of polysaccharides, proteins, lipids, and extracellular DNA, provides structural integrity to biofilms and protects microbial communities from environmental stresses [17]. In soil ecosystems, EPS enhances microbial survival by protecting cells against desiccation, heavy metals, osmotic stress, and antimicrobial compounds, thereby enabling microorganisms to persist under adverse environmental conditions [18]. EPS production also improved microbial communication through quorum sensing, enhanced adhesion and colonization of soil particles, increased stability of extracellular enzymes involved in nutrient transformations, and protection against environmental stresses such as drought and salinity [14]. These properties promote efficient microbial interactions and metabolic cooperation within the rhizosphere. EPS-producing bacteria such as Pseudomonas spp. have been reported to enhance soil aggregation and increase plant tolerance to abiotic stresses including drought and salinity, thereby improving soil resilience and overall ecosystem functioning (Figure 2).

Figure 2: Schematic representation of EPS functions and their contribution to soil health.

Biofilm Mediated Mechanisms for Improving Nutrient use Efficiency

Microbial biofilms in the rhizosphere represent highly organized microbial communities that enhance nutrient cycling and plant nutrient acquisition. These biofilms facilitate multiple biochemical and ecological processes that collectively improve nutrient use efficiency (NUE) in agricultural systems. Through cooperative metabolism, extracellular enzyme production, and enhanced microbial stability, biofilms regulate nutrient availability and retention in soil–plant systems [8,9]. Biofilm-forming microbial consortia often include nitrogen-fixing bacteria, phosphate-solubilizing microorganisms, and organic matter decomposers that interact synergistically within the extracellular polymeric substance (EPS) matrix to regulate nutrient dynamics in the rhizosphere [18,7]. The close spatial association of microorganisms in biofilms facilitates metabolic cooperation, leading to improved nutrient transformations and enhanced nutrient uptake by plants [19].

Nutrient solubilization, mobilization and transformation

Many biofilm-forming microorganisms, including Pseudomonas, Bacillus, and Rhizobium, produce organic acids, siderophores, and chelating compounds that solubilize otherwise unavailable nutrients such as phosphorus, zinc, and iron [20]. Within biofilms, these metabolic activities are intensified due to cooperative microbial interactions and localized concentration of metabolites, Phosphate-solubilizing bacteria embedded within biofilms release gluconic acid and other organic acids that convert insoluble phosphates into plant-available forms. These processes increase phosphorus uptake efficiency and reduce dependence on synthetic fertilizers. Studies have shown that Penicillium spp.,- Bradyrhizobium biofilms can release up to 88% of phosphorus from Eppawala rock phosphate, significantly enhancing soil phosphorus availability [21]. Additionally, periphyton biofilms in flooded rice ecosystems have been reported to increase bioavailable phosphorus fractions such as water-soluble P and Olsen-P by altering microenvironmental conditions including pH, oxygen concentration, and enzymatic activity [22].

Table 1: Biofilm-mediated mechanisms improving nutrient use efficiency in crops.

Biofilm mechanism	Microbial groups involved	Nutrient process affected	Impact on plant nutrient uptake / NUE	References
Extracellular polymeric substance (EPS) production	Pseudomonas, Bacillus, cyanobacteria	Soil aggregation and nutrient retention	Reduces nutrient leaching and improves nutrient availability in rhizosphere	[22]
Phosphorus solubilization	Bacillus, Pseudomonas, Penicillium	Organic acid production and mineral P solubilization	Increases availability of insoluble phosphates to plant roots	[20]
Biological nitrogen fixation	Rhizobium, Azotobacter, cyanobacteria	Conversion of atmospheric N_2 into plant-available forms	Enhances nitrogen availability and nitrogen use efficiency	[23]
Enzyme production and organic matter decomposition	Diverse rhizosphere microbial consortia	Mineralization of organic nutrients	Improves nutrient release from soil organic matter	[26]
Siderophore-mediated micronutrient mobilization	Pseudomonas, Bacillus	Iron and micronutrient chelation	Enhances micronutrient availability and uptake by plants	[27]
Microbial metabolic cooperation	Mixed microbial biofilm communities	Cross-feeding and cooperative nutrient cycling	Improves overall nutrient transformation efficiency	[19]
Stress tolerance through EPS matrix	Biofilm-forming rhizobacteria	Protection from drought and salinity	Maintains microbial activity and nutrient cycling under stress	[18]
Biofilm-based biofertilizer consortia	Cyanobacteria–fungal–bacterial consortia	Integrated nutrient mobilization	Improves crop growth, yield, and nutrient uptake	[29]

Biofilms also facilitate nitrogen transformations that directly influence NUE. Nitrogen-fixing bacteria such as Azotobacter and Rhizobium often form biofilms on root surfaces, where the structured microbial environment promotes efficient nitrogen fixation. Biofilm communities enhance nitrification and denitrification processes, contributing to balanced nitrogen cycling in soils. Biofilm architecture provides microenvironments with oxygen gradients that allow aerobic and anaerobic nitrogen processes to occur simultaneously. Such spatial organization enhances nitrogen retention and reduces nitrogen losses through volatilization or leaching [22-24]. Diazotrophic microorganisms embedded within biofilms convert atmospheric nitrogen into plant-available forms such as ammonia and nitrate. For example, a fungal–bacterial biofilm formed by Bradyrhizobium elkanii and Penicillium spp. has been shown to increase nitrogen mineralization and nitrogenase activity, resulting in higher concentrations of NH_4^+-N and NO_3^--N in soil. In addition to macronutrients, biofilms contribute to improved micronutrient availability in soil. Many biofilm-forming microorganisms produce siderophores that chelate iron and increase its solubility, while changes in soil redox conditions and microbial interactions near plant roots enhance the mobilization of micronutrients such as zinc and manganese. Application of biofilm-based inoculants such as Anabaena–Trichoderma and Anabaena–Azotobacter has been reported to increase soil organic carbon, microbial biomass, and micronutrient availability in agricultural systems. For instance, Kanchan et al. observed that an Anabaena–Trichoderma biofilm inoculant significantly increased zinc concentration and improved soil fertility in chrysanthemum cultivation [25]. Different mechanism involve in nutrient use efficiency are listed in Table 1 (Figure 3).

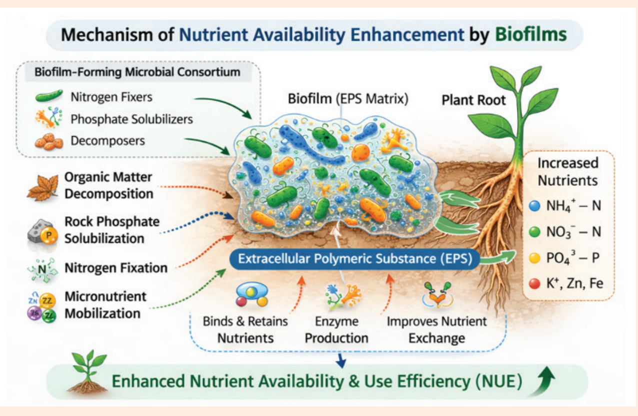

Figure 3: Mechanisms to enhance nutrient availability in soil by microbial biofilms.

Enhanced enzyme production and microbial metabolic synergy

Biofilm-forming microbes often exhibit elevated extracellular enzyme activity compared with planktonic cells. Enzymes such as phosphatases, proteases, cellulases, and dehydrogenases accelerate the decomposition of organic matter and nutrient mineralization. These enzymes release nutrients from organic residues, making them available for plant uptake. EPS binds mineral particles and organic matter, creating microhabitats that store nutrients and prevent their rapid loss from the rhizosphere [9]. Biofilms enable close physical association among diverse microbial species, promoting metabolic cooperation and cross-feeding interactions. For example, one microbial group may degrade complex organic compounds into simpler molecules that other microbes utilize for nutrient transformation processes [26]. Such synergistic interactions enhance overall nutrient cycling efficiency in soil ecosystems. Quorum sensing mechanisms further regulate microbial cooperation within biofilms. Signaling molecules coordinate gene expression related to nutrient acquisition, enzyme production, and biofilm stability [27]. These coordinated responses allow microbial communities to respond efficiently to changing nutrient availability in the rhizosphere. Biofilms provide protection against environmental stresses such as drought, salinity, and temperature fluctuations [28]. The EPS matrix retains moisture and protects microbial cells from desiccation, enabling sustained microbial activity even under adverse conditions.

Biofilms in Agricultural Systems

Biofilm-forming microbial inoculants have been successfully applied in several cropping systems to improve soil fertility, nutrient availability, and crop productivity. These biofilm-based formulations consist of compatible microbial consortia embedded within an extracellular polymeric substance (EPS) matrix, which enhances microbial survival, root colonization, and synergistic metabolic interactions in the rhizosphere. Such structured microbial communities often exhibit greater functional stability and efficiency compared with conventional single-strain biofertilizers, thereby contributing to improved nutrient cycling and plant growth. Prasanna et al. reported that inoculation with a Trichoderma-Bradyrhizobium biofilm significantly increased soil available nitrogen and microbial biomass carbon in soybean cultivation [29]. The enhanced microbial activity and nutrient transformations associated with the biofilm also resulted in higher soybean yield compared with uninoculated treatments, highlighting the potential of biofilm-based inoculants to improve both soil biological health and crop productivity. Rehman et al. further reported that application of biofilm-based biofertilizers significantly increased nitrogen, phosphorus, and potassium concentrations in chickpea shoots, indicating improved nutrient uptake efficiency and enhanced plant nutritional status [30]. The improved nutrient acquisition was attributed to increased microbial activity, efficient nutrient solubilization, and enhanced rhizosphere interactions facilitated by the biofilm matrix. Collectively, these findings highlight the considerable potential of biofilm-based biofertilizers as sustainable and environmentally friendly alternatives to conventional chemical fertilizers. By enhancing microbial interactions, nutrient transformations, and plant nutrient uptake, biofilm inoculants can contribute significantly to improving nutrient use efficiency and promoting sustainable agricultural production systems.

Challenges in Utilizing Biofilms for Nutrient Efficiency

Despite the promising role of microbial biofilms in improving nutrient cycling and nutrient use efficiency (NUE), several constraints still limit their large-scale application in agricultural systems.

a) Complexity and environmental variability: Biofilm formation and functionality are strongly influenced by environmental factors such as soil pH, temperature, moisture, and nutrient availability. Variations in these physicochemical conditions can affect microbial adhesion, EPS production, and quorum sensing processes that regulate biofilm development, resulting in inconsistent performance under field conditions. In addition, the succession of microbial populations within soil biofilms is highly dynamic and controlled by multiple biological and environmental interactions, which makes prediction of biofilm behaviour in agricultural soils challenging.

b) Competition with native soil microorganisms: Introduced biofilm-forming inoculants may compete with well-adapted indigenous microbial populations present in the rhizosphere. Native microorganisms often occupy ecological niches and root colonization sites more efficiently, which can limit the establishment, persistence, and functional expression of introduced biofilm strains.

c) Formulation and field application challenges: The development of stable biofilm-based microbial formulations that can maintain viability during storage, transport, and field application remains a significant technological challenge. Microbial consortia used in biofilms require suitable carriers, moisture conditions, and nutrient availability to remain active, and their performance may decline when exposed to fluctuating environmental stresses outside controlled laboratory conditions.

d) Monitoring and evaluation limitations: Another major limitation is the lack of efficient techniques for monitoring biofilm dynamics and microbial activity in complex soil environments. Unlike laboratory biofilms, soil biofilms are difficult to observe and quantify due to their heterogeneous structure and interactions with soil particles, organic matter, and plant roots. This limitation restricts the ability to accurately evaluate their persistence, nutrient transformation efficiency, and long-term ecological impacts in agricultural systems.

Technological Advances and Future Directions

Recent advances in molecular biology, genomics, and high-resolution imaging techniques have significantly improved the understanding of biofilm structure, microbial interactions, and functional dynamics in soil ecosystems. Modern approaches such as metagenomics, transcriptomics, and advanced microscopy allow detailed characterization of microbial consortia within biofilms, enabling researchers to identify functional genes involved in nutrient cycling and plant-microbe interactions. Emerging technologies such as synthetic biology and next-generation microbial inoculants are opening new opportunities to design engineered microbial consortia capable of forming stable biofilms and enhancing nutrient mobilization. These engineered biofilm-based biofertilizers can improve rhizosphere colonization, stimulate beneficial microbial populations, and enhance nitrogen and phosphorus use efficiency in crops. Another promising innovation is the development of nanotechnology-based fertilizers and bio-nanofertilizers, which enable controlled and targeted delivery of nutrients. Due to their high surface-area-to-volume ratio, nanofertilizers can release nutrients gradually, improve nutrient absorption by plants, and significantly reduce losses through leaching, volatilization, and runoff. These nano-enabled fertilizers also stimulate microbial activity and enhance rhizosphere processes, thereby improving nutrient use efficiency and crop productivity. Furthermore, the integration of biofilm technologies with precision agriculture tools-including geographic information systems (GIS), remote sensing, Internet of Things (IoT) sensors, and variable-rate fertilizer application-offers new possibilities for optimizing nutrient management. These technologies allow site-specific nutrient application based on real-time soil and crop data, reducing input costs while improving nutrient efficiency and environmental sustainability.

Conclusion

Microbial biofilms play a vital role in regulating nutrient dynamics in the rhizosphere and significantly contribute to improving NUE in agroecosystems. The structured microbial communities within the EPS matrix enhance nutrient solubilization, nitrogen fixation, enzyme activity, and micronutrient mobilization, leading to improved nutrient availability and plant uptake. In addition, biofilm formation strengthens soil aggregation, improves water retention, and enhances microbial resilience under environmental stresses, thereby supporting soil health and sustainable crop production. Despite their potential, challenges such as environmental variability, competition with native soil microbes, and formulation stability still limit the widespread application of biofilm-based technologies in agriculture. Developing stable biofilm-based microbial consortia, improving formulation technologies for field application, and integrating biofilm-based biofertilizers with precision nutrient management strategies need to explore. Such approaches can enhance nutrient efficiency, reduce dependence on chemical fertilizers, and promote sustainable agricultural production systems.

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