



Biofilm-Forming Bacteria: Their Role in Plant Growth Promotion and Sustainable Agriculture

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Bacterial biofilms are organized microbial communities attached to living or non-living surfaces and embedded in a self-produced extracellular matrix. This matrix commonly contains extracellular polysaccharides, proteins, extracellular DNA and associated substances. In agriculture, selected biofilm-forming plant growth-promoting bacteria (PGPB) are of interest because attachment and persistence near roots may support beneficial plant-microbe interactions. Depending on the strain and environment, these bacteria may also express traits such as indole-3-acetic acid production, phosphate solubilization, siderophore production and ACC deaminase activity. Biofilm formation can improve surface colonization and help bacteria tolerate certain stresses; however, biofilms are not always beneficial. Plant pathogens can use attachment and extracellular polymeric substances (EPS) to persist on plant tissues and contribute to disease. This article summarizes biofilm structure, formation, agricultural benefits, potential disadvantages, major characterization methods and research needs. It emphasizes that biofilm production alone is not proof of plant growth promotion and that candidate strains must be evaluated for efficacy, consistency and biosafety before agricultural application.

Keywords: Bacterial biofilm, extracellular polymeric substances, plant growth-promoting bacteria, rhizosphere, root colonization, sustainable agriculture

Introduction

Bacteria occur in soil, water, plant surfaces and many other environments. They may live as individual, free-floating cells (planktonic cells) or as surface-associated communities known as biofilms. A biofilm is not simply a group of cells stuck together: it is a structured community in which cells are embedded in a matrix produced by the microorganisms themselves. Biofilm formation can influence bacterial survival, communication, surface attachment and interactions with their surroundings. In agricultural systems, the rhizosphere—the narrow region of soil influenced by plant roots—is an important habitat for microorganisms. Beneficial bacteria that establish near roots may have more opportunities to interact with plants and contribute to nutrient acquisition or stress responses. At the same time, some plant-pathogenic bacteria also form biofilms, which can support colonization and persistence. Therefore, the significance of a biofilm depends on the identity and function of the organism, the plant host and the environmental conditions.

Structure and composition of a bacterial biofilm

The extracellular matrix is a defining feature of many bacterial biofilms. Its composition varies among species and with growth conditions, but commonly includes extracellular polymeric substances (EPS), proteins, extracellular DNA (eDNA), water, ions and trapped organic or inorganic compounds. Polysaccharides can help cells adhere to surfaces and maintain matrix structure. Proteins may act as adhesins or structural components, while

eDNA can contribute to matrix stability and cell-to-cell interactions. The hydrated matrix can retain substances and create local conditions that differ from the surrounding environment. For plant-associated bacteria, EPS may support attachment to root surfaces, microbial aggregation and water retention around cells. These properties may help selected strains persist under some conditions, including limited water availability or salinity. Nevertheless, EPS production is not sufficient by itself to establish that a bacterium will promote plant growth; other beneficial traits and successful plant association must also be demonstrated.

How biofilms develop

Biofilm formation is a dynamic process. A commonly used model describes five connected stages:

Initial reversible attachment. Free-living cells approach and temporarily attach to a surface. Surface properties, motility and environmental conditions can influence this step.

Irreversible attachment. Cells establish a more stable association, often involving surface structures, adhesins and extracellular materials.

Microcolony formation. Attached cells multiply and form clusters; matrix material helps hold the developing community together.

Maturation. The biofilm develops a more complex structure, with variation in nutrients, oxygen and metabolic activity across the community. Cell-to-cell signalling may regulate some behaviours.

Dispersal. Some cells or aggregates leave the established biofilm and may colonize new surfaces.

These stages are a useful framework rather than a universal sequence. The speed, architecture and regulation of biofilm formation vary with bacterial strain, surface, nutrient availability, pH, temperature, salinity and interactions with other microorganisms.

Agricultural importance of biofilm-forming PGPB

Plant growth-promoting bacteria are selected microorganisms that can benefit plant growth through one or more biological mechanisms. Some PGPB also form biofilms, and this combination is being explored for agricultural use. Biofilm formation may help a beneficial strain attach to root surfaces and remain near the plant, creating opportunities for the expression of plant growth-promoting functions.

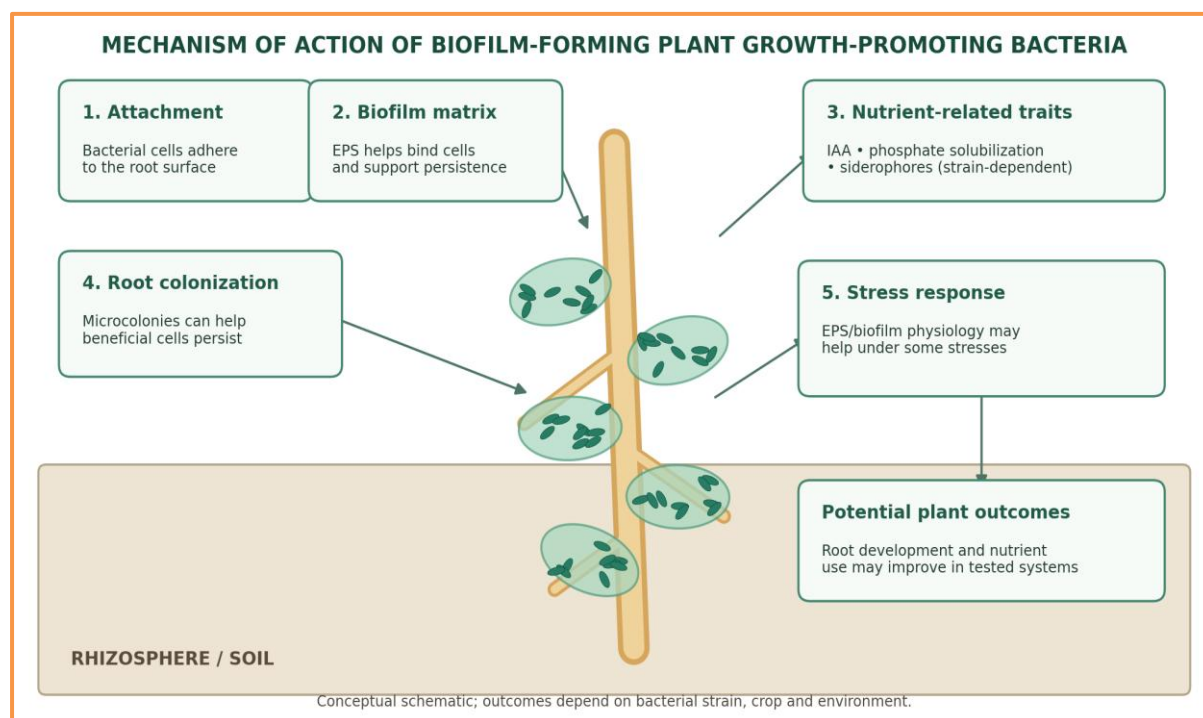


Figure 1. Conceptual mechanism of action of biofilm-forming plant growth-promoting bacteria (PGPB).

As illustrated in Figure 1, selected beneficial bacteria attach to root surfaces and produce an extracellular polymeric substance (EPS) matrix that can support cell aggregation and persistence. Depending on the strain, associated plant growth-promoting traits—such as indole-3-acetic acid (IAA) production, phosphate solubilization and siderophore production—may contribute to plant nutrition or root development. Biofilm formation alone does not guarantee a beneficial plant response; these effects require validation in plant-based and field studies.

Root colonization and persistence

Attachment to root surfaces can help bacteria establish a population in the rhizosphere. Persistence is important because a strain must survive competition with native microorganisms and changing soil conditions to interact consistently with a crop. However, strong biofilm formation in a laboratory plate does not necessarily predict successful colonization in soil or on roots.

Plant growth-promoting traits

Trait	Main function	Possible agricultural relevance
Indole-3-acetic acid (IAA) production	Produces a plant auxin that can influence root development.	May alter root architecture depending on concentration, plant species and conditions.
Phosphate solubilization	Makes some poorly soluble phosphorus sources more available.	May contribute to plant phosphorus nutrition.
Siderophore production	Produces molecules that bind iron with high affinity.	Supports bacterial iron acquisition and may affect competition with other microbes.
ACC deaminase activity	Breaks down ACC, a precursor of ethylene.	May help moderate some stress-associated effects of ethylene.
EPS production	Contributes to the extracellular matrix and surface interactions.	May support attachment, aggregation and stress tolerance in some environments.
Catalase activity	Breaks down hydrogen peroxide.	May contribute to bacterial protection against oxidative stress.

These functions are strain-specific and should be tested independently. Biofilm formation, IAA production, phosphate solubilization or siderophore production alone cannot establish that a strain will improve crop yield. Plant-based experiments are needed to verify the combined outcome.

Potential advantages

Improved surface attachment. Biofilms can help cells remain associated with roots or other surfaces, potentially supporting microbial establishment.

Stress tolerance. The matrix and biofilm-associated physiology may improve tolerance to selected environmental stresses, although protection is not universal.

Local retention of nutrients and water. The matrix may retain water, ions and organic compounds near cells and influence local microbial activity.

Potential contribution to sustainable agriculture. Well-characterized beneficial strains may be developed as microbial inoculants that complement other crop-management practices.

Environmental applications. Biofilms can retain microorganisms in treatment systems and support selected biological processes, such as pollutant transformation.

Disadvantages and limitations

Biofilm formation is not inherently beneficial. Some plant-pathogenic bacteria use surface attachment and EPS-associated structures to establish persistent populations on plant tissues. In certain diseases, extracellular material can contribute to colonization and, in vascular infections, may be associated with impaired water movement. Outside agriculture, unwanted

biofilms can cause persistent contamination in food-processing equipment and water systems, and may create fouling in industrial systems. For beneficial agricultural products, practical limitations include variable performance among soil types and crops, competition with native microorganisms, reduced viability during storage, formulation difficulties and inconsistent field results. A strain must also be assessed for identity and biosafety. These challenges mean that laboratory screening is an early step, not a substitute for greenhouse and field evaluation.

Methods used to characterize biofilms

Method	What it indicates	Key limitation
Congo red agar screening	Colony phenotypes associated with matrix-related traits in some organisms.	Colour is not a universal or definitive confirmation of biofilm formation.
Crystal violet microplate assay	Estimates total attached biomass through retained stain and optical density.	Does not distinguish living from dead cells or show three-dimensional structure.
Tube adherence assay	Preliminary observation of attached material on tube surfaces.	Often subjective and less suitable for precise quantitative comparisons.
Microscopy (e.g., confocal or scanning electron microscopy)	Can reveal biofilm structure or surface-associated features.	Requires equipment and careful sample preparation; images alone may not establish function.
Viable-cell counts or molecular analysis	Can provide information about culturable cells or selected genes.	Each method measures a different property and should be interpreted accordingly.

In a crystal violet assay, the optical density of stained material is used as an estimate of attached biomass. Some studies classify isolates by comparing sample optical density with a cutoff derived from negative controls (OD_c). The exact wavelength, controls, replicates, calculation and classification boundaries should be reported clearly. Results from different protocols should not be compared as though they were identical.

Future prospects and research needs

Future work should connect laboratory biofilm measurements with root colonization and plant performance under realistic growing conditions. Researchers can compare biofilm-forming and weakly biofilm-forming isolates while independently measuring plant growth-promoting traits. Further priorities include studying EPS composition, evaluating performance under drought or salinity, testing compatibility with other beneficial microorganisms, improving formulation and shelf life, and conducting replicated pot and field trials. Strain identification and biosafety assessment should accompany efficacy testing.

Conclusion

Biofilm formation is an important bacterial lifestyle that influences attachment, persistence and interactions with the environment. In agricultural microbiology, selected biofilm-forming PGPB may offer opportunities to support root colonization and plant growth when they possess suitable beneficial traits. However, biofilms can also contribute to plant disease and other forms of persistent contamination. The practical value of a bacterial isolate must therefore be established through careful characterization, plant-based testing, field validation and biosafety assessment. A balanced understanding of both the benefits and limitations will help guide the responsible development of microbial technologies for sustainable agriculture.

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