Biofilms in hydroponic infrastructure

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***Abstract*—Biofilms are organised surface-associated microbial communities embedded in self-produced extracellular material, rather than merely visible slime. This distinction matters in hydroponics because pipes, channels, reservoirs and root-zone surfaces remain wet and can retain microorganisms beyond those detected in bulk nutrient solution. This paper synthesises evidence on biofilm development, persistence, sanitation relevance and microbial transport in closed and recirculating hydroponic infrastructure. Biofilm formation proceeds through attachment, extracellular matrix production, maturation and dispersal, creating persistent surface habitats that can release microorganisms into circulating water. Hydroponic evidence identifies infrastructure as a possible inoculum reservoir and recirculating solution as a route for microbial dissemination. Established multispecies communities may complicate sanitation and facilitate pathogen attachment. However, a detected biofilm is not proof of plant disease, because hydroponic microbial communities can contain beneficial as well as harmful organisms. Biofilm assessment should therefore integrate surface condition, microbial identity, circulation pathways and plant-health evidence [1], [2], [3], [4].**

I. Introduction

Biofilms in hydroponic infrastructure should not be understood simply as slime, residue or an incidental deposit. A biofilm is a community of microorganisms attached to a surface and embedded in extracellular material produced by those organisms. Its development commonly progresses from reversible attachment to stable attachment, matrix production, maturation and dispersal. This sequence creates a structured habitat whose behaviour can differ from that of freely suspended microorganisms in water. The distinction is important for hydroponic systems because continuously wetted pipes, channels, reservoirs and root-zone surfaces can support surface-associated communities. Hygiene assessment must consequently consider both the nutrient solution and the microbial habitats retained on infrastructure [2].

Hydroponic infrastructure can affect microbial persistence because channels, pipes, tanks and reservoirs may serve as inoculum reservoirs. Shared nutrient solution can then provide a route through which microorganisms are transported among connected components. Inadequate sanitation may permit persistence across crop cycles, rather than restricting microbial presence to an isolated contamination event. This evidence does not establish that every wetted surface is contaminated or that every retained community is harmful. It does establish that a water-only assessment can overlook infrastructure-associated sources capable of retaining microorganisms and reintroducing them into circulation [1].

The significance of biofilms requires caution as well as attention. In closed soilless systems, biofilms can facilitate pathogen attachment, while microbial communities may also contribute disease-suppressive activity. Biofilm presence therefore does not by itself demonstrate plant disease or identify a causal organism. This paper defines biofilm structure and development, examines the relationship between surface persistence, sanitation and transport, and explains why a biofilm observation must be separated from disease diagnosis [3].

II. Background and Scope

Biofilm persistence follows from the interaction of surface attachment, conditioning films, extracellular matrix formation and maturation. These processes can stabilise communities on wetted materials and support multispecies organisation. Mature biofilms may also show resistance to biocides that differs from the response expected from microorganisms suspended in solution. Dispersal is equally relevant because organisms retained within a biofilm can later enter the surrounding water. In hydroponic systems, this mechanism provides a basis for regarding flow surfaces as part of the microbial environment. The available evidence supports persistence and release mechanisms generally, although it does not quantify the contribution of every infrastructure surface to transport in a particular system [2].

The surface and resident microbial community can influence sanitation difficulty. Evidence from closed soilless horticulture indicates that resident biofilm-forming bacteria can facilitate pathogen attachment on PVC surfaces. Naturally formed multispecies biofilms may also require substantially stronger sanitation than simpler communities. This finding directs attention beyond an isolated target organism towards the condition of the surface and the community already occupying it. It does not provide a universal sanitation protocol or demonstrate that PVC infrastructure necessarily causes disease. Rather, it supports the conclusion that established surface communities can alter sanitation performance and should be considered when interpreting hygiene outcomes [3].

The scope of biofilm interpretation must include both potential risk and biological variation. Closed hydroponic systems may contain resident biofilm-forming bacteria, conditions favourable to pathogen attachment and disease risks, yet they may also contain beneficial microbial activity. A surface-associated community is therefore evidence of a microbial habitat, not a sufficient causal explanation for plant symptoms. The central explanatory gap is to connect biofilm mechanisms with hydroponic hygiene without making unsupported claims about disease. This paper addresses that gap through evidence synthesis rather than by reporting a new experiment [4].

III. Core Concepts and Mechanisms

Microbial identity constrains what can be inferred from a biofilm observation. In soilless systems, beneficial and pathogenic bacteria can occur within the same genus, so broad taxonomic recognition cannot reliably determine whether a surface community is harmful. Nor can visible surface growth identify the organisms present, their viability or their role in plant symptoms. A detected biofilm should therefore be interpreted as a surface-associated microbial habitat that warrants contextual investigation. It is not a sufficient diagnostic endpoint. Disease attribution requires more specific information about microbial identity and plant condition than can be supplied by attached biomass alone [5].

Recirculation provides the hydraulic setting in which local persistence may become system-wide. Shared recirculating hydroponic solutions can disseminate pathogens and other contaminants, creating a need for contamination control and disinfection. This supports concern that microorganisms released from an infrastructure-associated community could enter broader circulation. However, the available evidence provides limited direct measurement of how persistent biofilms on particular pipes, reservoirs or root-zone surfaces contribute to transport. The supported inference is conditional: recirculation can amplify dissemination when relevant microorganisms are present, but the contribution of a specific infrastructure component should not be assumed without system-specific evidence [6].

Biofilms should not be classified only as hazardous deposits. Surface attachment and extracellular matrix production explain why a community can persist and why sanitation may become difficult, but these characteristics do not establish whether its members are harmful or beneficial to plants. Biofilms can have both harmful and beneficial plant-associated roles. For hydroponic infrastructure, the useful question is whether a resident community affects microbial survival, pathogen attachment, sanitation response or circulation in a way relevant to the system. This framing recognises biofilms as organised habitats while preserving a separate evidentiary burden for plant disease claims [2].

IV. Evidence Synthesis

The evidence supports a linked model of surface persistence and waterborne movement. General biofilm evidence explains attachment, matrix formation, maturation and dispersal. Hydroponic evidence identifies channels, pipes, tanks and reservoirs as potential reservoirs for persistent inoculum, while recirculation can provide a pathway for pathogen dissemination. Together, these findings explain why infrastructure is more than passive equipment. A community retained on a wetted surface can remain relevant even when a bulk-solution sample appears temporarily acceptable. The strongest support concerns the connection between persistence and dissemination, rather than a quantified transport contribution from one specified biofilm location [1], [2], [4].

Sanitation should consequently be treated as a system property rather than a treatment applied only to nutrient solution. Surface-associated organisms and freely suspended organisms may not respond identically to control measures. Naturally established multispecies biofilms may require stronger sanitation, while hydroponic treatment approaches involve trade-offs. These findings justify attention to both infrastructure and circulating solution, but they do not establish one optimal treatment method, intensity or schedule. The evidence is insufficient to specify a universal threshold for unacceptable biofilm presence or a universally effective removal approach. Sanitation decisions must therefore remain responsive to the particular system and its observed conditions [3], [4].

Diagnostic interpretation remains the key constraint on an infrastructure-centred approach. Resident biofilm-forming bacteria can facilitate pathogen attachment, and recirculation can distribute relevant organisms. At the same time, closed systems can contain beneficial microbial activity. Biofilm presence should therefore prompt investigation of hygiene, microbial composition and plant condition, rather than immediate attribution of disease causation. This distinction is particularly important because beneficial and pathogenic bacteria may occur within the same genus. A defensible interpretation combines surface observations with organism-level evidence and plant-health information [3], [4], [5].

V. Practical Implications and Limitations

Hydroponic hygiene assessment should consider flow surfaces as well as nutrient solution. Pipes, channels, tanks and reservoirs can retain inoculum, while shared nutrient solution can distribute microorganisms among connected locations. Surface-associated persistence may therefore remain relevant even where water quality is the principal routine concern. This does not imply that every component requires the same sanitation response. It does imply that surfaces and solution should be assessed as linked elements of one microbial environment, especially where inadequate sanitation could allow microbial persistence across crop cycles [1].

Verification of sanitation should be distinguished from diagnosis of plant disease. Resident biofilm-forming bacteria can facilitate pathogen attachment, and naturally formed multispecies communities can complicate sanitation. Yet closed hydroponic systems can also contain beneficial microbial activity. Assessment should therefore distinguish surface persistence, microbial identity, sanitation response and plant-health evidence. The available evidence does not establish a standard detection protocol, a universal acceptable biofilm threshold or a fixed causal relation between biofilm detection and crop symptoms. These limitations require cautious interpretation rather than the assumption that biofilms are either always hazardous or always irrelevant [3], [4].

The principal evidence gap is quantitative linkage within operating hydroponic systems. Existing evidence establishes biofilm development and persistence mechanisms, identifies infrastructure as a potential reservoir and supports recirculation as a transport pathway. It provides less direct evidence attributing a transport outcome or plant disease event to a specific infrastructure-associated biofilm. Future validation

should therefore connect surface communities, microbial identification, sanitation outcomes, circulation pathways and plant observations within the same system. This would clarify when a persistent community is operationally significant and when it is only one component of a broader microbial environment [1], [2], [6].

VI. Conclusion

Biofilms in hydroponic infrastructure are structured surface-associated microbial communities embedded in extracellular material, not merely visible slime. Their progression through attachment, matrix production, maturation and dispersal explains how microorganisms can persist on pipes, channels, reservoirs and root-zone surfaces. These habitats matter because infrastructure can retain inoculum, established communities can complicate sanitation and recirculating solution can support microbial movement [1], [2], [3].

Biofilm presence is not proof of plant disease. Hydroponic microbial communities can contain beneficial and harmful organisms, and reliable disease attribution requires evidence beyond surface observation. The highest-value next work is system-specific validation linking biofilm persistence, microbial identity, sanitation response, circulation behaviour and plant outcomes [4], [5].

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References

[1] S. Scott and C. Villouta, "Dissolved oxygen limitation and pythium root rot in strawberry nft systems: Mechanisms, research gaps, and prospects for substrate-free production," *Frontiers in Plant Science*, 2026.

[2] M. H. Muhammad, A. L. Idris, X. Fan, Y. Guo, Y. Yu, X. Jin, J. Qiu, X. Guan, and T. Huang, "Beyond risk: Bacterial biofilms and their regulating approaches," *Frontiers in Microbiology*, 2020. [Online]. Available: https://doi.org/10.3389/fmicb.2020.00928

[3] M. T. Naseem and W. Zaman, "Root-zone engineering in closed soilless horticulture: From plant physiology to sensor-guided control," *Horticulturae*, 2026.

[4] S. Wang, Y. Kleiner, S. M. Clark, V. Raghavan, and B. Tartakovsky, "Review of current hydroponic food production practices and the potential role of bioelectrochemical systems," *Reviews in Environmental Science and Bio/Technology*, 2024.

[5] I. A. Lakhiar, H. Yan, T. N. Syed, C. Zhang, S. A. Shaikh, M. Rakibuzzaman, and R. B. Vistro, "Soilless agricultural systems: Opportunities, challenges, and applications for enhancing horticultural resilience to climate change and urbanization," *Horticulturae*, 2025.

[6] M. Elakrouch, M. Mohaddab, A. Rachid, and M. H. Jijakli, "Soilless agriculture at a crossroads: Strengths, challenges, and prospects of hydroponics, aquaponics, and bioponics in relation to precision farming," *Sustainability*, 2025.