The hydroponic rhizosphere

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***Abstract*—The hydroponic rhizosphere is the biologically active interface surrounding roots in soil free culture, where exudates, microorganisms, dissolved resources, and oxygen interact continuously. Although hydroponic systems are often described through bulk nutrient and dissolved oxygen measurements, the evidence indicates that conditions at the root surface can diverge materially from values measured in the circulating solution. This paper synthesises current evidence on three linked questions: how the rhizosphere should be defined in hydroponics, how root exudates and microbial activity influence local oxygen demand, and why bulk dissolved oxygen readings may not fully describe root surface oxygenation. Across the literature, roots are shown to modify local chemistry through exudation, ion uptake, pH change, and interactions with microbial communities, establishing a distinct root influenced zone in soilless systems. Evidence from recirculating and nutrient film technique systems further shows that exudate accumulation, microbial metabolism, root biomass, and biofilm development can increase local biological oxygen demand and generate oxygen gradients near roots. The practical implication is that hydroponic root health depends not only on maintaining acceptable bulk dissolved oxygen, but also on recognising microscale heterogeneity and the biological processes that shape oxygen conditions in the immediate root environment.**

I. Introduction

In hydroponic culture, the rhizosphere is best understood not as a vague region around roots, but as a dynamic interface in which roots actively reshape their chemical and biological surroundings through exudation, nutrient uptake, and interaction with microorganisms. General rhizosphere literature describes this zone as one where root derived compounds alter chemistry, influence nutrient availability, and recruit or suppress microbial groups, making it a functional environment rather than a simple geometric boundary [1]. This definition remains relevant in soil free systems because the absence of soil does not remove root influence; instead, it can make the root driven interface more directly dependent on solution flow, oxygen supply, and biological turnover. The implication is that hydroponic management must treat the root zone as an active microenvironment rather than assuming that bulk solution values represent root experience [1], [2], [3].

The oxygen question becomes especially important when hydroponic systems mature and biological activity intensifies. Evidence from strawberry nutrient film technique systems shows that hypoxia is linked not only to physical constraints on oxygen supply, but also to changing exudate patterns, increasing root biomass, and rising microbial load, all of which raise biological oxygen demand near roots [4]. This means that oxygen conditions in the hydroponic rhizosphere are co produced by plant metabolism and associated microbial respiration. A system may therefore appear chemically acceptable in the reservoir while root surface conditions deteriorate because oxygen is being consumed locally faster than it is replenished. Framing hydroponic oxygen management in rhizosphere terms helps explain why root disorders can develop even when standard operating measurements appear reasonable [4], [5].

A further complication is that the rhizosphere is spatially and temporally heterogeneous. Rhizosphere processes emerge from coupled biological, physical, and chemical interactions, so conditions at one point on a root system may differ from conditions only millimetres away [1]. In hydroponics, this heterogeneity is likely to be shaped by flow path, root mat density, exudate concentration, microbial colonisation, and local diffusion limits. The present paper therefore argues that the hydroponic rhizosphere should be analysed as a microscale oxygen environment embedded within a larger circulating solution. It first defines the rhizosphere in soilless culture, then explains the mechanisms by which exudates and microorganisms affect oxygen demand, and finally evaluates why bulk dissolved oxygen measurements provide an incomplete description of root surface conditions [1], [4], [6].

II. Background and Scope

Recent reviews of soilless cultivation increasingly frame hydroponics as a system for regulating the root environment rather than merely delivering nutrients. This framing is important because it places nutrient supply, gas exchange, and microbial communities within the same analytical field, and it recognises rhizosphere microorganisms as direct contributors to crop health [2]. In that sense, the hydroponic rhizosphere is not an imported soil concept awkwardly applied to water culture; it is a necessary concept for describing how roots create a local zone of altered chemistry and biology within a managed aqueous environment. The literature also indicates that moisture status and aeration strongly affect microbial activity in soilless systems, reinforcing the view that oxygen conditions cannot be separated from biological dynamics around roots [2].

More direct hydroponic evidence comes from substrate free strawberry nutrient film technique research, where the rhizosphere is effectively expressed through the interaction of oxygen status, altered exudation, microbial load, and pathogen activity at the root surface [4]. This work is valuable because it shows the rhizosphere concept operating in a fully hydroponic setting rather than in container media or soil analogies. Root

zone conditions are shaped by the plant, by the microbes supported or suppressed by root derived compounds, and by the hydraulic geometry through which oxygenated solution moves. That combination shows clearly that, in soil free culture, roots still generate a biologically and chemically distinct zone whose processes matter for plant performance and disease risk [4], [7].

The central scope limitation in the existing literature is that oxygen is often discussed at the system scale, whereas root health is determined at much smaller scales. Studies and reviews commonly report dissolved oxygen targets, aeration practices, or reservoir level measurements, but the more detailed NFT evidence argues that bulk dissolved oxygen values can be poor proxies for the conditions experienced by roots when root mats, temperature, channel geometry, and pathogen interactions modify local oxygen dynamics [4], [8]. This paper therefore does not attempt a full microbiological survey of the hydroponic root zone. Its narrower purpose is to explain how biological activity in the hydroponic rhizosphere affects oxygen demand and why reader level interpretation should distinguish between bulk solution measurements and the microscale environment adjacent to roots [4].

III. Core Concepts and Mechanisms

The first core concept is that the hydroponic root zone becomes biologically and chemically distinct because roots are sources of carbon compounds and other exudates that structure nearby metabolism. Reviews of hydroponic food production describe root exudates as substrates for rhizosphere microbial metabolism and note that recirculating systems can also support pathogen spread, algae growth, and other chemistry altering processes [7]. These interactions mean that the rhizosphere is not defined solely by nutrient depletion around roots; it is also shaped by the metabolic activity that root derived compounds enable. Once established, this biologically active zone can alter local pH, redox conditions, and oxygen use patterns, making the immediate root surface environment a distinct process domain within the larger hydroponic circuit [7], [9].

The second mechanism concerns oxygen demand itself. Evidence from hydroponic reviews indicates that exudates can accumulate in closed or recirculating systems and support microbial growth, while microbes and algae can modify dissolved oxygen through their own metabolism [7]. In practical terms, root exudation adds labile substrates to the immediate root environment, and microbial populations using those substrates consume oxygen as part of aerobic metabolism. Where root biomass is large, flow is constrained, or biofilms develop on surfaces, oxygen replenishment may lag behind local demand. This mechanism aligns with the stronger NFT evidence showing that biological oxygen demand rises with root mass and microbial load [4], [7]. The implication is that hydroponic oxygen stress can emerge from a mismatch between local consumption and transport, not simply from inadequate reservoir aeration.

The third concept is that exudates modify rhizosphere chemistry in ways that indirectly influence oxygen related behaviour. Broader rhizosphere evidence shows that exudates can alter pH, solubilise nutrients, chelate micronutrients, and recruit beneficial microbes [1]. Although this evidence does not on its own prove oxygen depletion, it establishes the rhizosphere as a chemically engineered space produced by the plant. In hydroponics, such chemical modification matters because it changes which microbial processes are favoured and how intensely the local community may respire. Root induced pH shifts and exudation driven chemistry differences have also been documented in soilless substrates, supporting the more general point that root adjacent conditions can diverge from bulk solution chemistry [9]. Thus, oxygen balance in the hydroponic rhizosphere should be interpreted as part of a coupled chemistry biology system rather than as an isolated gas management problem.

IV. Evidence Synthesis

Across the accepted evidence, the strongest support for biologically mediated oxygen demand comes from studies that link oxygen consuming processes to organic inputs and microbial turnover. Review work on bioponics shows that aerobic microbial degradation and nitrification both require oxygen and can be disrupted when excess organics shift the balance of microbial processing [10]. Although this literature is not centred on the root surface, it provides an important boundary condition for hydroponic interpretation: whenever dissolved or particulate organics are available, oxygen demand becomes partly biological rather than purely plant respiratory. This principle helps explain why the hydroponic rhizosphere is vulnerable to local oxygen stress, because roots continuously release exudates into a zone that can also host dense microbial populations [7], [10].

The broader soilless cultivation literature supports this interpretation but usually with less spatial precision. Reviews emphasise that moisture conditions, aeration, and substrate or solution environment strongly shape microbial activity, and they recognise hydroponic microbial communities as consequential for plant growth and health [2]. What these sources contribute is system level context: root environment regulation is inseparable from biological regulation. What they do not fully resolve is the microscale path from exudation to oxygen depletion at the root surface. For that reason, they are most persuasive when read alongside more direct hydroponic rhizosphere evidence rather than alone. Their practical value lies in showing that oxygen management and microbial management are interdependent tasks, even if the exact local gradients remain undercharacterised in many production settings [2], [11].

The evidence for bulk versus microscale divergence is similarly cumulative. Soilless reviews discuss how aeration, substrate properties, and microbial communities shape the root environment, but they generally stop short of demonstrating that bulk dissolved oxygen measurements are insufficient descriptors of root surface oxygenation [2]. Stronger support

comes when this broader literature is combined with studies showing local chemistry shifts near roots, biofilm related gradients near surfaces, and NFT specific arguments that channel geometry and root mat development create local oxygen conditions different from the circulating solution [4], [7], [9]. Taken together, the evidence supports the conclusion with moderate confidence that bulk dissolved oxygen remains useful for operational control, but it should not be treated as a complete measure of the oxygen status that actually governs rhizosphere function and root stress.

V. Practical Implications and Limitations

A practical implication of this synthesis is that hydroponic oxygen assessment should be understood as a transport problem as well as a concentration problem. Analogous evidence from soil aeration research shows that bulk water status alone does not determine root zone aeration because diffusivity and pore connectivity control how oxygen actually moves to roots [12]. Hydroponics is physically different from soil, but the analogy is instructive: local geometry and transport pathways matter. In water based systems, root mat density, boundary layers, and channel flow can perform an equivalent limiting function by slowing oxygen renewal at the surface where demand is highest. The limitation is that this support is indirect, so it strengthens the logic of microscale oxygen heterogeneity without replacing the need for direct hydroponic measurement studies [4], [12].

A second implication is that claims of precise control in soilless farming should be interpreted cautiously when discussing the rhizosphere. Review literature rightly notes that hydroponics enables close regulation of the root environment and highlights microbiome functions in these systems [11]. Yet the same evidence is broad, and it does not show that operators can directly observe or stabilise the biological oxygen conditions at the root surface. Control at the reservoir or system level is therefore not identical to control at the microscale where roots and microbes interact. This distinction matters for troubleshooting because acceptable system readings may coexist with local oxygen deficits, especially in recirculating systems with active microbial metabolism, mature root systems, or persistent surface colonisation [7], [11].

A third implication concerns monitoring and interpretation. Reviews of hydroponics, aquaponics, and related soilless systems provide useful bulk dissolved oxygen thresholds and discuss precision management, but they do not by themselves establish the biology and chemistry of the rhizosphere in enough detail to predict local oxygen behaviour [8]. Other hydroponic contexts, including wastewater systems, show that roots can support an active rhizosphere involving oxygenation processes, exudates, and near root transformations, reinforcing the generality of a biologically active root interface [13]. Even so, evidence remains uneven across crop types and system designs. The most defensible conclusion is not that all hydroponic rhizospheres behave identically, but that biological activity can materially alter oxygen conditions around roots, and that better validation is needed to connect system level sensors with root surface realities [8], [13].

VI. Conclusion

The hydroponic rhizosphere is a root influenced biological and chemical zone in which exudates, microbial communities, nutrient transformations, and oxygen transport interact continuously [1], [2], [7]. The evidence reviewed here shows that this zone is present in soil free culture, that root exudates and associated microbial metabolism can increase local biological oxygen demand, and that root surface conditions may differ from bulk dissolved oxygen values measured elsewhere in the system [4], [7], [9]. The central argument is therefore that hydroponic oxygen status should not be reduced to a single bulk number. It is better understood as a local balance between oxygen supply and biologically mediated demand in the immediate vicinity of roots.

The main limitation of the evidence base is that direct hydroponic measurements of microscale rhizosphere oxygen remain less common than broader reviews of aeration, microbiomes, or nutrient management [8], [10], [11]. Future work of highest value would connect bulk monitoring with finer scale measurements near roots across contrasting hydroponic designs, especially where root mats, recirculation, and microbial accumulation are likely to intensify oxygen gradients [4]. Until that evidence is expanded, the most scientifically defensible practical message is clear: hydroponic root health depends on the biological activity of the rhizosphere as well as on the nominal oxygen condition of the bulk solution.

Acknowledgment

The author used artificial intelligence tools to assist with manuscript drafting and revision, and with LaTeX and bibliography preparation. The author reviewed all AI-assisted output and remains responsible for the final content.

References

[1] N. Joshi, R. Kaur, and T. Nawaz, "The soil-root nexus: how soil health shapes plant nutrient uptake and food nutritional security," *Plant and Soil*, 2026.

[2] A. Tuxun, Y. Xiang, Y. Shao, J. E. Son, M. Yamada, S. Yamada, K. Tagawa, B. Baiyin, and Q. Yang, "Soilless cultivation: Precise nutrient provision and growth environment regulation under different substrates," *Plants*, 2025.

[3] E. Fathidarehnijeh, M. Nadeem, M. Cheema, R. Thomas, M. Krishnapillai, and L. Galagedara, "Current perspective on nutrient solution management strategies to improve the nutrient and water use efficiency in hydroponic systems," *Canadian Journal of Plant Science*, 2024.

[4] S. Scott, "Dissolved oxygen limitation and pythium root rot in strawberry nft systems: mechanisms, research gaps, and prospects for substrate-free production," *Scott S and Villouta C (*, 2026.

[5] C. Grierson, E. Nielsen, T. Ketelaar, and J. Schiefelbein, "Root hairs," *The Arabidopsis Book*, 2014.

[6] A. Fussy and J. Papenbrock, "An overview of soil and soilless cultivation techniques-chances, challenges and the neglected question of sustainability," *Plants*, 2022.

[7] 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.

[8] 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*, 2026.
[9] J. Huang, P. R. Fisher, W. R. Argo, K. Y. Jeong, and J. Altland, "Macronutrient solubility in response to the ph of soilless container substrates," *Journal of Soil Science and Plant Nutrition*, 2025.
[10] I. Szekely and M. H. Jijakli, "Bioponics as a promising approach to sustainable agriculture: A review of the main methods for producing organic nutrient solution for hydroponics," *Water*, 2022.
[11] 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.
[12] B. Pragg, M. M. T. Lakshani, T. K. K. C. Deepagoda, K. Cameron, H. Di, T. J. Clough, S. Carrick, B. Elberling, and K. Smits, "Identification of plant soil water and soil aeration corequisites: A management tool," *Soil Science Soc of Amer J*, 2024.
[13] C. Mai, A. Mojiri, S. Palanisami, A. Altaee, Y. Huang, and J. L. Zhou, "Wastewater hydroponics for pollutant removal and food production: Principles, progress and future outlook," *Water*, 2023.