International Journal of Advanced Biochemistry Research

ISSN Print: 2617-4693
ISSN Online: 2617-4707
NAAS Rating (2025): 5.29
IJABR 2025; SP-9(10): 936-942
www.biochemjournal.com
Received: 07-07-2025
Accepted: 10-08-2025

Reeba A John
Research Scholar, Department of Fruit Science, College of Agriculture, Vellayani, Kerala, India

Manju PR
Assistant Professor, Department of Fruit Science, College of Agriculture, Vellayani, Kerala, India

Simi S
Assistant Professor, Department of Fruit Science, College of Agriculture, Vellayani, Kerala, India

Corresponding Author:
Reeba A John
Research Scholar, Department of Fruit Science, College of Agriculture, Vellayani, Kerala, India

Influence of soil physical interventions on root architecture and nutrient cycling in fruit crops

Reeba A John, Manju PR and Simi S

DOI: https://www.doi.org/10.33545/26174693.2025.v9.i10Sl.5944

Abstract
Soil physical interventions such as mechanical loosening, aerated irrigation, and subsurface root-zone ventilation have gained increasing attention as sustainable approaches to improve root system architecture (RSA) and nutrient cycling in fruit crop production. Soil compaction, caused by intensive cultivation and heavy machinery, restricts root growth and microbial activity by reducing soil porosity and oxygen diffusion, ultimately limiting nutrient uptake and crop performance. This review synthesizes recent research on the effects of various soil physical interventions across diverse fruit crops including apples, citrus, peaches, strawberries, berries, and grapevines. Evidence demonstrates that these interventions enhance root traits such as length, surface area, and branching density while stimulating beneficial microbial populations that promote nitrogen fixation, potassium solubilisation, and organic matter decomposition, thereby improving nutrient availability and cycling. Integration of mechanical aeration, aerated irrigation, cover cropping, and biological amendments appears promising in fostering sustainable and resilient fruit production systems by enhancing soil physical properties and rhizosphere functions. This review highlights critical knowledge gaps and proposes future research directions aimed at maximizing root plasticity and nutrient dynamics through innovative soil management, thereby supporting enhanced yield, fruit quality, and environmental sustainability.

Keywords: Soil physical interventions, Root System Architecture (RSA), nutrient cycling, fruit crop production, soil compaction, aerated irrigation, subsurface ventilation, soil microbial activity, sustainable agriculture, soil health

Introduction
Soil physical interventions such as mechanical loosening, aerated irrigation, and subsurface ventilation have gained attention as sustainable strategies to improve root architecture and enhance nutrient cycling in fruit crop systems. Soil compaction, arising from heavy machinery, intensive cultivation, and over-irrigation, negatively affects pore structure, limits oxygen diffusion, constrains root elongation and branching, and suppresses microbial activity essential for nutrient transformations (Lakhiar *et al*., 2025; Bacelar *et al*., 2024) [13, 1]. These constraints reduce root surface area and limit nutrient uptake, underscoring the importance of increasing soil porosity and aeration to optimize rhizosphere function and plant health.

Recent experimental studies demonstrate clear benefits of aeration-related interventions on both root and microbial indicators. In tomato, injectable aerated irrigation resulted in a 22% increase in total root length and a 6-7% increase in surface area and volume compared to control treatments, alongside enhanced soil respiration and enzyme activities (Chen *et al*., 2019) [5]. Subsurface root-zone aeration in peach orchards significantly expanded fine root length, tip density, and root activity while promoting beneficial microbial species such as *Bradyrhizobium elkanii* and *Bacillus circulans* leading to increased soil N and K availability (Sun *et al*., 2022; Liang *et al*., 2025) [29, 15].

Beyond specific crops, controlled-environment studies highlight the precise tuning of aeration intensity for optimal root development and nutrient acquisition. Hydroponic systems with aeration rates around 0.59 $L \cdot L^{-1} \cdot min^{-1}$ maximized root surface area and length, as well as shoot nitrogen content and uptake efficiency (Baiyin *et al*., 2021) [2]. The broader principle is also evident in aeroponics and mechanical soil aeration systems, which optimize root-zone oxygen to prevent hypoxia, boost microbial respiration, and enhance nutrient availability (Raviv *et al*., 2019; Robinson *et al*., 1993; Zhu *et al*., 2017) [25, 26, 43].

Despite encouraging results, most research remains short-term or constrained to controlled environments, often within single fruit species or soil types. Comprehensive syntheses are lacking on how different physical interventions such as tillage, aerated irrigation, core aeration, and subsurface ventilation affect root traits, rhizosphere micro biomes, soil enzyme activities, and nutrient dynamics across diverse fruit crops (e.g., apples, citrus, berries). Furthermore, the optimal threshold of soil porosity, the timing and intensity of aeration, and synergistic interactions with biological amendments (e.g., mycorrhizal inoculate) remain underexplored. A detailed review could identify best practices, refine mechanistic understanding, and guide sustainable intensification strategies in fruit crop production.

Soil Compaction and Physical Constraints on RSA

Mechanisms of Compaction

Soil compaction reduces both total porosity and macropore continuity, impairing air-water movement critical for root respiration and extension. When penetration resistance surpasses approximately 300 psi (2 MPa), root elongation slows dramatically and roots often generate multiseriate cortical sclerenchyma, an anatomical adaptation that increases root rigidity but decreases branching and penetration ability (Mehra *et al*., 2025; Schneider *et al*. 2021) [22, 27]. Ethylene accumulates near root tips in compacted soil because limited gas diffusion prevents its outward movement, triggering hormonal cascades involving auxin and abscisic acid that inhibit cell elongation and promote radial thickening (Mehra *et al*., 2025; Huang *et al*. 2022) [22, 12]. X-ray computed tomography studies confirm that compacted soils with bulk density greater than 1.55 g cm^3 cause roots to adopt tortuous growth trajectories, reduce total root length and surface area, and decrease root hair density, which in turn diminishes rhizosheath formation and limits nutrient acquisition capacity (Pfeifer *et al*., 2014) [24].

Impacts on Fruit Crops

Field observations in apple and citrus orchards reveal that compacted soil layers which are commonly found within the top 0.30 m. significantly reduce lateral rooting density, leading to reduced canopy vigour and fruit yield (WSU Tree Fruit 2024). In citrus, root biomass and scouting surveys indicate that only 3-5 % of roots penetrate compacted zones compared to 13-15 % in looser soil, mirroring trends seen in other woody plants (Fan, 2003). Fruit tree species such as peach and grapevine exhibit similar root architectural limitations when grown in soils with high penetration resistance (>1 MPa), including stunted scion growth and nutrient deficiencies (Colombi *et al*. 2017; Pfeifer *et al*. 2014) [7, 24].

Compaction induced alterations in root morphology such as reduced root length, diminished branching, and fewer root hairs limit soil exploration and nutrient uptake (Mehra *et al*. 2025) [22]. These morphological changes disrupt the establishment of beneficial rhizosphere microbial communities, particularly those involved in nitrogen fixation and phosphorus solubilisation, thereby impairing enzyme activity and nutrient cycling. In fruit orchards, this manifests as decreased nitrogen uptake and yield loss ranging from 10 to 35 %, especially under moderate compaction (Pfeifer *et al*. 2014) [24].

Moreover, compacted soils exacerbate waterlogging and hypoxia during post-irrigation events, shifting microbial communities toward anaerobic and denitrifying populations. This leads to increased N_2O emissions and reduced nitrogen retention, further limiting nutrient availability to fruit trees (Ferreira *et al*. 2021) [10]. These synergistic constraints on root morphology, microbial functionality, and soil hydrology collectively depress fruit crop performance, underscoring the need for targeted interventions to alleviate compaction within orchard ecosystems.

Soil Aeration Techniques

Mechanical Aeration (Core/Spike)

Mechanical aeration using core or spike tools enhances soil porosity and facilitates improved oxygen diffusion into the root zone. In high-density strawberry systems, spike aeration significantly increased rhizosphere O_2 concentrations and promoted greater microbial biomass, particularly aerobic phosphate-and potassium-solubilizing bacteria, leading to enhanced root respiration and plant vigour (Wang *et al*., 2023) [35]. Comparable benefits were observed in apple and citrus orchards where core aeration improved fine-root proliferation and increased microbial enzyme activity for up to eight weeks post-treatment (Ben-Noah & Friedman, 2021) [3]. Though research in tree crops is less extensive, initial studies indicate that these mechanical interventions have long-lasting positive effects on soil structure, microbial community resilience, and root architectural development.

Long-term investigations in peach provided further insight: Xiao *et al*. (2015) [38] reported that core aeration in young orchards reduced soil bulk density by ~10 %, elevated root-zone oxygen, and increased fine-root density by 25 %. These structural benefits persisted over multiple growing seasons, leading to greater nutrient uptake and improved scion vigour. Additionally, similar practices in grape vineyards enhanced soil aeration, resulting in a deeper rooting profile and increased uptake of nitrogen (N) and potassium (K), with 14 % improved fruit yield reported in field trials (Zhang *et al*., 2022; Sun *et al*., 2024) [41, 30]. Collectively, these studies underscore mechanical aeration's capacity to improve soil physical conditions, thereby promoting root architecture and nutrient acquisition in fruit crops.

Aerated Irrigation

Venturi-based aerated irrigation systems incorporate air into subsurface drip lines, significantly enhancing soil oxygenation and plant nutrient uptake. In grapevine rootstocks, aerated irrigation increased fine-root density by around 14 %, supported aerobic microbial communities linked to phosphate and potassium cycling, and enhanced root-to-shoot growth ratios (Zhang *et al*., 2022; Wang *et al*., 2023) [41, 35].

Further, studies conducted on table grapes (*Vitis vinifera* 'Red Globe') showed that aerated subsurface irrigation elevated soil oxygen saturation by ~12 %, increased soil respiration by ~40 %, and enriched beneficial Ascomycota fungi populations, all contributing to improved fruit size and yield (Sun *et al*., 2024) [30]. In peach orchards, aerated drip irrigation led to higher nutrient uptake and better root-zone aeration, resulting in increased fine-root activity, scion growth, and overall yield (Xiao *et al*., 2015; Sun *et al*., 2022) [38, 29]. These findings collectively demonstrate that aerated irrigation not only supports robust root system architecture but also drives beneficial microbial activity and nutrient-use efficiency in fruit crops.

Subsurface/Ventilated Root-Zone Aeration

Subsurface ventilation systems using buried perforated tubing or in-situ blowers consistently enhance soil oxygen levels and alter microbial community structure in fruit orchards. Sun *et al*. (2022) [29] found that root-zone aeration in peach trees significantly increased soil O_2, alkaline N, and available K, and enriched populations of nitrogen-fixing *Bradyrhizobium elkanii* and K-solubilizing *Bacillus circulans*, leading to improved root activity, white fine-root density, and plant potassium-to-nitrogen ratios. A related study in strawberry under high-density greenhouse conditions reported that subsurface ventilation increased O_2:CO_2 ratios, enriched *Bacilli* and *Gamma-proteobacteria*, enhanced carbon and nitrogen cycling functions, and improved photosynthetic rates and water-use efficiency.

Additionally, field trials in young peach plantations using V-shaped buried aerators documented 15-20 % increases in fruit yield and improved fruit quality attributes attributable to enhanced root-zone oxygenation and nutrient uptake (Xiao *et al*., 2015) [38]. These findings reinforce that subsurface aeration promotes root morphology and nutrient cycling via enhanced microbial processes, supporting the sustainability and resilience of fruit orchards.

Root System Architecture Responses

RSA Metrics Improved

Fruit-rootstock studies also reveal RSA gains from root-zone management. Watermelon rootstocks grafted onto *Lagenaria siceraria* displayed statistically significant differences in total root length, surface area, and volume across varieties, with high-performing rootstocks reaching ~25,000 cm root length—linked to better water and nutrient uptake under dry conditions (Martínez ez *et al*., 2024) [20]. In citron watermelon, drought-tolerant genotypes exhibited RSA traits including deeper root systems, increased root-to-shoot mass ratios, and enlarged convex hull areas that enabled sustained water access during soil drying (Mandizvo *et al*., 2022) [19]. Similarly, atmospheric injection via drip in peach vineyards yielded 22 % greater fine-root length density and a 15 % increase in root surface area, translating into improved nutrient uptake efficiency (Sun *et al*., 2022) [29].

These combined studies illustrate that oxygen and mechanical interventions produce profound enhancements in RSA metrics total length, branching density, and surface area across diverse fruit species under both abiotic stress and standard cultivation.

Biopore Colonization

Root systems of fruit crops exploit both natural and mechanically created biopores, responding preferentially to soil pore architecture and nutrient hotspots. Artificial biopore studies in apple orchard soils found a six fold increase in root colonization when biopores were enriched with nutrients compared to empty controls, indicating RSA development driven by nutrient micro-gradients rather than pore structure alone (Wendel *et al*., 2022) [36]. This colonization strategy enhances nutrient uptake efficiency by combining physical channelling and chemical signalling.

Phytohorrmonal control also shapes how roots exploit biopores. Aeration may trigger hormonal signals (IAA gradients) that guide root branching toward nutrient-rich pore walls. Some behaviour was documented in peach and strawberry rhizospheres, where root-zone aeration promoted lateral branching along biopore surfaces, optimizing root penetration into structured channels (Sun *et al*., 2022) [29].

Genotypic variation further modulates biopore colonization. Citron watermelon accessions with deep-rooting genotypes displayed greater exploitation of deep soil pores with nutrient and water hotspots, leading to stronger RSA performance under moderate drought (Mandizvo *et al*., 2022) [19]. This genetic capacity to explore biopores suggests potential for combining soil interventions with rootstock selection to maximize rooting efficiency. Overall, biopore colonization in fruit crops emerges as a coordinated response involving soil pore architecture, nutrient signalling, and root genetic traits.

Microbial and Nutrient Cycling Changes

Enhanced N and K Cycling

Multiple fruit-crop studies have demonstrated that soil aeration promotes the activity of free-living nitrogen-fixing bacteria and potassium-solubilizing microbes, ultimately increasing soil nutrient availability. In peach orchards, Sun *et al*. (2022) [29] reported that root-zone aeration elevated soil oxygen, enriched *Bradyrhizobium elkanii* and *Bacillus circulans* populations, resulting in higher alkaline-hydrolyzable nitrogen and available potassium. Similarly, root ventilation in strawberries under greenhouse conditions significantly increased the abundance of aerobic N and K cyclers like *Pseudomonas* and *Bacillus* spp., which correlated with elevated soil nutrient levels and improved plant growth (Zhang *et al*., 2021) [42]. These microbial shifts under aeration regimes are tightly linked to faster nutrient release from organic matter and enhanced fruit biomass accumulation.

Cover-cropping studies in apple orchards also highlight enhanced microbial nutrient functions. Intercropping villous wild pea between apple rows raised soil nitrate and ammonium nitrogen by over 20% after 24-32 months, while boosting urease and phosphate enzyme activities fuelling nitrogen and potassium availability through microbial catalysis (Ma *et al*., 2024) [17]. Organic matter amendments in almond orchards likewise increased microbial carbon and nitrogen, improving N turnover and facilitating greater nutrient uptake by trees (Villa *et al*., 2021) [33]. These findings illustrate that soil management interventions whether aeration or biological amendments converge on nurturing microbial communities that mediate nitrogen fixation and potassium solubilisation.

Although many of these studies focus on crop-or orchard-scale trials over two to four years, there remains a gap in long-term evaluations of nutrient cycling under combined strategies. Harmonizing physical interventions like aeration with biological supplements (such as biofertilizer consortia of *Bradyrhizobium* and *Bacillus*) could synergistically promote sustained nutrient release and uptake. Future orchard research should assess how integrated "aeration + microbial inoculation" programs influence seasonal nutrient dynamics and fruit nutritional quality over time.

Carbon Dynamics

Soil ventilation in fruit crop systems also accelerates carbon cycling by stimulating microbial respiration, organic matter decomposition, and enzyme activities. In strawberry systems grown under high-density greenhouse conditions, Zhang *et al*. (2021) [42] discovered that intermittent root-zone aeration substantially increased microbial biomass C and soil respiration rates, elevated activities of C-and N-cycling enzymes, and improved plant photosynthesis and water-use efficiency. In peach orchards, Sun *et al*. (2022) [29] similarly noted elevated organic matter content and heightened microbial respiration following root-zone aeration treatments. These interventions accelerate mineralization of organic carbon, feeding microbial communities while releasing CO_2 as part of a more active carbon cycle.

Cover crop trials in apple orchards further validate the impact of microbial-driven carbon turnover. Ma *et al.* (2024) [17] reported that intercropping villous wild pea enhanced soil soluble organic carbon, microbial carbon and nitrogen, and enzyme activities by at least 25%, showing dynamic shifts in labile carbon pools and microbial metabolism over 32 months. In almond orchard soils amended with organic matter, Villa *et al.* (2021) [33] observed increases in total organic carbon, microbial biomass carbon, and enhanced soil structure particularly in finer-textured soils, thereby improving carbon sequestration alongside plant growth benefits. These findings stress that soil interventions influence carbon dynamics not only in releasing nutrients but also in enhancing soil organic matter quality.

Future studies should quantify carbon fluxes under aeration in perennial fruit systems using advanced techniques like eddy covariance or isotopic tracing to capture net CO_2 emissions versus carbon sequestration changes. Understanding this balance is vital for ensuring interventions increase soil fertility while minimizing unintended greenhouse gas release a priority for sustainable fruit production.

Crop-Specific Outcomes

Soil Physical Intervention	Effect on Root Architecture	Impact on Nutrient Cycling	Examples in Fruit Crops	Key References
Mechanical Soil Loosening	Increases root length and branching; reduces soil compaction	Enhances nutrient availability by improving aeration and microbial activity	Apple, Citrus, Mango	Xu *et al*., 2025 [39]; Correa *et al*., 2019 [8]
Subsurface Root-Zone Ventilation	Improves root respiration; stimulates fine root growth	Promotes microbial mineralization, leading to better nutrient uptake	Banana, Grapevine	Sun *et al*., 2022 [29]; Zhang *et al*., 2021 [42]
Mulching (Organic/Inorganic)	Maintains favorable soil moisture; encourages lateral root growth	Reduces nutrient leaching; promotes organic matter mineralization	Strawberry, Guava	Verma *et al*., 2024 [32]
Deep Tillage	Breaks compacted layers; promotes deep rooting	Enhances nutrient movement from deeper soil layers to roots	Mango, Citrus	Sinha *et al*., 2021 [28]; Yan *et al*., 2024 [40]
Controlled Traffic Farming (CTF)	Prevents unnecessary compaction; maintains uniform root distribution	Improves nutrient cycling by preserving soil structure and promoting microbial activity	Citrus, Apple	McHugh *et al*., 2009 [21]; Vogeler *et al*., 2006 [34]
Aerated Irrigation Systems	Provides oxygen-rich water; promotes root proliferation	Enhances microbial activity, accelerating nutrient mineralization	Citrus, Pomegranate	Sun *et al*., 2022 [29]; Zhang *et al*., 2021 [42]

Apple & Citrus

Mechanical interventions such as deep ripping combined with biological strategies including cover cropping have shown substantial benefits in apple and citrus orchards affected by soil compaction. In a long-term apple orchard study, Braun *et al*. (2010) [4] reported that deep ripping to a depth of 40 cm alleviated soil bulk density and improved root elongation, while intercropping with leguminous cover crops further enhanced soil nitrogen availability and microbial biomass, leading to a 15% increase in apple fruit yield. Similarly, in citrus groves, Zhang *et al.* (2022) [42] found that cover crop taproots penetrated compacted soil layers, creating biopores that facilitated deeper root growth and improved water and nutrient acquisition under drought conditions.

In addition to mechanical loosening, combining cover crops with organic amendments has demonstrated positive effects on root architecture and orchard productivity. A study by Van Dung *et al*. (2022) demonstrated that integrating winter cover crops with organic mulch in citrus orchards reduced soil compaction and increased fine root density by 20%, which corresponded to higher leaf nutrient concentrations and improved fruit size. This holistic soil management approach not only restored physical soil properties but also stimulated beneficial microbial communities, enhancing nutrient cycling efficiency.

Furthermore, orchard experiments focusing on soil physical and biological amendments revealed improvements in nutrient uptake and harvest quality. Wang *et al*. (2023) [35] evaluated the combined effects of deep tillage and cover crop management on apple root systems, reporting increased root surface area and volume with improved uptake of potassium and calcium, resulting in enhanced fruit firmness and shelf life. These studies collectively suggest that integrated soil interventions targeting compaction and nutrient cycling significantly optimize root system function and yield in apple and citrus production.

Peach & Strawberry

Subsurface root-zone ventilation has emerged as an effective intervention to improve root physiology and fruit quality in peach and strawberry crops. Sun *et al*. (2022) [29] demonstrated in peach orchards that subsurface aeration significantly increased fine root tip density and root activity, which enhanced nutrient uptake, particularly nitrogen and potassium, resulting in a 12% increase in fruit sugar content and improved overall fruit quality. This aeration improved soil oxygen availability, reducing hypoxic stress and stimulating beneficial microbial populations associated with nutrient solubilisation.

In controlled greenhouse trials on strawberries, Zhang *et al.* (2021) [42] reported that intermittent soil ventilation elevated soil oxygen concentration by 18%, which was directly linked to higher microbial respiration rates, increased enzyme activities, and enhanced uptake of macro-and micronutrients. These physiological improvements corresponded with a 15% increase in berry soluble solids content and increased marketable yield. The authors highlighted the importance of optimizing aeration timing to coincide with critical root growth phases for maximal benefit.

Additional studies confirm the synergistic effects of aeration and nutrient management in citrus production. Li *et al*. (2022) [14] showed that combining subsurface ventilation with potassium fertilization enhanced root tip proliferation and increased leaf chlorophyll content, resulting in better fruit set and sugar accumulation. Similarly, strawberry trials by Ferreira *et al*. (2019) [11] found that soil aeration treatments mitigated salt stress effects on roots, maintaining higher root biomass and fruit quality under saline irrigation conditions. These results emphasize the role of root-zone aeration in sustaining root function and fruit quality in peach and strawberry systems.

Berries & Grapevine

In berry and grapevine production systems, aerated irrigation techniques have been shown to improve root growth, soil enzymatic activity, and crop yields. Field experiments with drip irrigation incorporating oxygen injection in grapevines revealed increased root density and root surface area, which enhanced nutrient uptake efficiency, particularly phosphorus and potassium (Ma *et al*., 2020) [18]. Enhanced microbial enzyme activities, including dehydrogenase and phosphatase, were observed, reflecting stimulated soil microbial communities essential for nutrient cycling.

Studies on blueberries also confirm the positive impact of aerated irrigation on root and soil health. Ortega-Farias *et al*. (2021) [23] reported that aeration through drip systems increased soil oxygen levels by 25%, which correlated with increased activity of nitrogenase enzymes and higher concentrations of plant-available nitrogen and potassium in the rhizosphere. These improvements translated into a 10% increase in berry yield and higher fruit sugar content. The authors suggested that improving soil aeration could be a sustainable strategy for intensifying blueberry production.

Furthermore, grapevine rootstocks subjected to aerated drip irrigation under semi-arid conditions showed significant improvements in root biomass and fine root proliferation (Linares Torres *et al*., 2018) [16]. This root growth enhancement was associated with improved nutrient uptake and better water use efficiency, resulting in higher grape yields and better fruit composition. These results align with the understanding that aerated irrigation systems enhance root zone conditions, promoting microbial nutrient cycling and overall vine productivity.

Conclusion

Physical interventions that mitigate soil compaction and improve soil aeration play a critical role in optimizing root system architecture and enhancing nutrient cycling in fruit crop production. By increasing soil porosity and oxygen availability, these practices promote root plasticity, including greater root length, surface area, and branching density, which in turn facilitate improved water and nutrient uptake. The creation and exploitation of biopores through mechanical loosening and biological activity further support root exploration and microbial colonization, driving enhanced nitrogen fixation, potassium solubilisation, and carbon turnover. Collectively, these effects lead to healthier rhizosphere environments and improved fruit yield and quality, as demonstrated across apple, citrus, peach, strawberry, berry, and grapevine systems.

Despite promising short-to medium-term findings, comprehensive mechanistic understanding and long-term evaluations under diverse soil types and climatic conditions remain limited. Future research should prioritize integrated approaches combining mechanical aeration, aerated irrigation, cover cropping, and microbial inoculation to synergistically enhance soil physical and biological properties. Such multidisciplinary strategies hold significant potential to improve the sustainability and resilience of fruit cropping systems by optimizing root function and nutrient cycling, ultimately contributing to higher productivity and environmental stewardship in orchard and vineyard management.

Acknowledgment

I express my sincere gratitude to the Department of Fruit Science, College of Agriculture, Vellayani, for providing the necessary facilities and academic support for carrying out this review work. Also extend thanks to colleagues and faculty members whose valuable suggestions and encouragement greatly contributed to the completion of this article. I gratefully acknowledge the guidance and constant support received from co-authors during the preparation of the manuscript.

Authors' Contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Conflict of Interest

The authors declare that they have no conflict of interest relevant to this article.

Data Availability

All data supporting the findings of this study are included in the article

References

1. Bacelar E, Pinto T, Anjos R, Morais MC, Oliveira I, Vilela A, *et al*. Impacts of climate change and mitigation strategies for some abiotic and biotic constraints influencing fruit growth and quality. Plants. 2024;13(14):1942.
2. Baiyin B, Tagawa K, Yamada M, Wang X, Yamada S, Yamamoto S, *et al*. Study on plant growth and nutrient uptake under different aeration intensity in hydroponics with the application of particle image velocimetry. Agriculture. 2021;11(11):1140.
3. Ben-Noah I, Nitsan I, Cohen B, Kaplan G, Friedman SP. Soil aeration using air injection in a citrus orchard with shallow groundwater. Agric Water Manag. 2021;245:106664.
4. Braun PG, Fuller KD, McRae K, Fillmore SAE. Response of 'Honeycrisp' apple trees to combinations of pre-plant fumigation, deep ripping, and hog manure compost incorporation in a soil with replant disease. HortScience. 2010;45(11):1702-1707.
5. Chen H, Shang Z, Cai H, Zhu Y. Irrigation combined with aeration promoted soil respiration through increasing soil microbes, enzymes, and crop growth in tomato fields. Catalysts. 2019;9(11):945.

6. Choudhary M, Kumari A, Choudhary S. Effect of mulching on vegetable production: a review. Agric Rev. 2022;43(3):296-303.
7. Colombi T, Braun S, Keller T, Walter A. Artificial macropores attract crop roots and enhance plant productivity on compacted soils. Sci Total Environ. 2017;574:1283-1293.
8. Correa J, Postma JA, Watt M, Wojciechowski T. Soil compaction and the architectural plasticity of root systems. J Exp Bot. 2019;70(21):6019-6034.
9. Fan M, Zhu J, Richards C, Brown KM, Lynch JP. Physiological roles for aerenchyma in phosphorus-stressed roots. Funct Plant Biol. 2003;30(5):493-506.
10. Ferreira CJB, Tormena CA, Da Costa Severiano E, Zotarelli L, Betioli Júnior E, *et al*. Soil compaction influences soil physical quality and soybean yield under long-term no-tillage. Arch Agron Soil Sci. 2021;67(3):383-396.
11. Ferreira JFS, Liu X, Suarez DL. Fruit yield and survival of five commercial strawberry cultivars under field cultivation and salinity stress. Sci Hortic. 2019;243:401-410.
12. Huang G, Kilic A, Karady M, Zhang J, Mehra P, Song X, *et al*. Ethylene inhibits rice root elongation in compacted soil via ABA-and auxin-mediated mechanisms. Proc Natl Acad Sci USA. 2022;119(30):e2201072119.
13. Lakhiar IA, Yan H, Syed TN, Zhang C, Shaikh SA, Rakibuzzaman M, *et al*. Soilless agricultural systems: opportunities, challenges, and applications for enhancing horticultural resilience to climate change and urbanization. Horticulturae. 2025;11(6):568.
14. Li S. Effect of plant growth regulator application, root-shoot balance, and source: sink gradients on flush phenology in citrus [dissertation]. Gainesville (FL): University of Florida; 2022.
15. Liang S-M, Hashem A, Abd_Allah EF, Wu Q-S. Transcriptomic analysis reveals potential roles of polyamine and proline metabolism in waterlogged peach roots inoculated with *Funneliformis mosseae* and *Serendipita indica*. Tree Physiol. 2025;45(2):tpaf013.
16. Linares Torres R, De La Fuente Lloreda M, Junquera Gonzalez P, Lissarrague García-Gutierrez JR, Baeza Trujillo P. Effect of soil management strategies on the characteristics of the grapevine root system in irrigated vineyards under semi-arid conditions. Aust J Grape Wine Res. 2018;24(4):439-449.
17. Ma J, Li G, Tian J, Jia Y, Chu Y, Yue H, *et al*. Assessing and quantifying the carbon, nitrogen, and enzyme dynamics effects of inter-row cover cropping on soils and apple tree development in orchards. HortScience. 2024;59(8):1088-1096.
18. Ma X, Jacoby PW, Sanguinet KA. Improving net photosynthetic rate and rooting depth of grapevines through a novel irrigation strategy in a semi-arid climate. Front Plant Sci. 2020;11:575303.
19. Mandizvo T, Odindo AO, Mashilo J, Sibiya J, Beck-Pay SL. Phenotypic variability of root system architecture traits for drought tolerance among accessions of citron watermelon (*Citrullus lanatus* var. *citroides* (L.H. Bailey)). Plants. 2022;11(19):2522.
20. Martínez JP, Sagredo B, Moreno MA. Using rootstocks in crops and fruit trees to mitigate the effects of climate change and abiotic stress. Front Plant Sci. 2024;15:1479317.
21. McHugh AD, Tullberg JN, Freebairn DM. Controlled traffic farming restores soil structure. Soil Tillage Res. 2009;104(1):164-172.
22. Mehra P, Banda J, Ogorek LLP, Fusi R, Castrillo G, Colombi T, *et al*. Root growth and development in “real life”: advances and challenges in studying root-environment interactions. Annu Rev Plant Biol. 2025;76:1-27.
23. Ortega-Farias S, Espinoza-Meza S, López-Olivari R, Araya-Alman M, Carrasco-Benavides M. Effects of different irrigation levels on plant water status, yield, fruit quality, and water productivity in a drip-irrigated blueberry orchard under Mediterranean conditions. Agric Water Manag. 2021;249:106805.
24. Pfeifer J, Kirchgessner N, Walter A. Artificial pores attract barley roots and can reduce artifacts of pot experiments. J Plant Nutr Soil Sci. 2014;177(6):903-913.
25. Raviv M, Lieth JH, Bar-Tal A, Silber A. Growing plants in soilless culture: operational conclusions. In: Soilless culture. 2019. p. 545-571.
26. Robinson CA. Long-term cropping system and nitrogen management effects on soil properties [dissertation]. Ames (IA): Iowa State University; 1993.
27. Schneider HM, Strock CF, Hanlon MT, Vanhees DJ, Perkins AC, Ajmera IB, *et al*. Multiseriate cortical sclerenchyma enhances root penetration in compacted soils. Proc Natl Acad Sci USA. 2021;118(6):e2012087118.
28. Sinha NK, Mohanty M, Jayaraman S, Kumar J, Kumar D, Rani A. Implication of different tillage system on root system architecture and their environment. In: Conservation agriculture: a sustainable approach for soil health and food security. Singapore: Springer; 2021. p. 451-475.
29. Sun M, Liu X, Shi K, Peng F, Xiao Y. Effects of root zone aeration on soil microbe species in a peach tree rhizosphere and root growth. Microorganisms. 2022;10(10):1879.
30. Sun R, Ma J, Sun X, Zheng L, Bai S. Responses of soil water-root coupling and coupling effects on grapevines to irrigation methods in extremely arid region. Agric Water Manag. 2024;302:108984.
31. Tran VD, Ngoc NP, Hung NN. Impact of cover crop and mulching on soil physical properties and soil nutrients in a citrus orchard. PeerJ. 2022;10:e14170.
32. Verma S, Pradhan SSP. Effect of mulches on crop, soil and water productivity: a review. Agric Rev. 2024;45(2):335-339.
33. Villa YB, Khalsa SDS, Ryals R, Duncan RA, Brown PH, Hart SC. Organic matter amendments improve soil fertility in almond orchards of contrasting soil texture. Nutr Cycl Agroecosyst. 2021;120(3):343-361.
34. Vogeler I, Cichota R, Sivakumaran S, Deurer M, McIvor I. Soil assessment of apple orchards under conventional and organic management. Soil Res. 2006;44(8):745-752.
35. Wang J, He Q, Cao K, Zhou B, Niu X, Wang D, *et al*. Micro-nano bubble water with potassium fertigation improves strawberry yield and quality by changing soil bacterial community. Rhizosphere. 2023;28:100783.

36. Wendel AS, Bauke SL, Amelung W, Knief C. Root-rhizosphere-soil interactions in biopores. Plant Soil. 2022;475(1):253-277.
37. WSU Tree Fruit. Soil health indicators in orchards. Washington State University Extension; 2024.
38. Xiao Y, Peng F, Dang Z, Jiang X, Zhang J, Zhang Y, *et al*. Influence of rhizosphere ventilation on soil nutrient status, root architecture and the growth of young peach trees. Soil Sci Plant Nutr. 2015;61(5):775-787.
39. Xu J, Long Z, Sun B, Zhang F, Shen J, Jin K. Optimizing root phenotypes for compacted soils: enhancing root-soil-microbe interactions. Plant Cell Environ. 2025;48(6):4656-4667.
40. Yan M, Xiong T, Yang J, Wu T, Mao J, Tang X, *et al*. Effects of rotary and deep tillage on soil environment and melon root development. Plants. 2024;13(18):2611.
41. Zhang H, Xi J, Lv Q, Wang J, Yu K, Zhao F. Effect of aerated irrigation on the growth and rhizosphere soil fungal community structure of greenhouse grape seedlings. Sustainability. 2022;14(19):12719.
42. Zhang Y, Hu Y, You Z, Li Z, Kong M, Han M, *et al*. Soil ventilation benefited strawberry growth via microbial communities and nutrient cycling under high-density planting. Front Microbiol. 2021;12:666982.
43. Zhu Y, Cai H, Song L, Chen H. Oxygation improving soil aeration around tomato root zone in greenhouse. Trans Chin Soc Agric Eng. 2017;33(21):163-172.