PJS

Pharaonic Journal of Science
https://pjscience.org/

SPBH

Review article

Sustainable Horticulture: Assessing the Efficacy of Organic and Bio-Fertilizers in Supporting Tree Health and Production-Review

[1]Mustafa Natheer Mustafa, [1]Waad S. faizy, [2]Mohammed Salim Ahmed Al-Alaf, [2]Samir Farhan Ayoub

[1]Northern Technical University - Agricultural Technology College - Department of Plant Production Technologies, Iraq

[2]Northern Technical University - Agricultural Technology College - Desertification Combating Department, Iraq

[*]**Corresponding author E-mail:** Mustafa.n.m1989@ntu.edu.iq

DOI: https://doi.org/10.71428/PJS.2026.0104

Abstract

Chemical fertilizers and pesticides have greatly enhanced agricultural productivity over the last half-century, but their unselective application has been responsible for environmental pollution, soil degradation, pest resistance, and human health issues. Hence, there has been increasing interest in environment-friendly methods like Integrated Pest Management (IPM), biofertilizers, and organic farming. Biofertilizers—consisting of beneficial microorganisms like bacteria, fungi, and algae—increase nutrient availability due to nitrogen fixation and mineral dissolution, and provide a sustainable source of chemicals. Organic farming and organic amendments enhance soil fertility, microbial diversity, and ecosystem services, and sustain or enhance crop quality. Organic systems, in earlier research, were shown to have yields equal to conventional systems under favorable conditions, but it requires more labor and higher input costs. Recent research has highlighted the application of biofertilizers and microbial inoculants in tree crops, namely citrus, apricot, olive, pomegranate, and apple, and has noted improved growth, yield, fruit quality, nutrient uptake, and disease resistance. A combination of synergistic inputs like amino acids, humic substances, PGPR, mycorrhizal fungi, and organic amendments further increases crop productivity and stress tolerance. Emerging technologies such as nanomaterials, microbial endophytes, and controlled environment agriculture hold further promise for sustainable productivity. Long-term experiments reaffirm that mixed and organic fertilization methods equal or surpass the nutritional and yield capacity of inorganic fertilizers, but these have lower environmental effects. It indicates the potential of organic and biological inputs in sustainable horticultural production, especially for perennial tree crops, and stresses their role in addressing future food demand against altered climatic and demographic scenarios.

Keywords: organic fertilizers, biofertilizers, tree health, PGPR, sustainable agriculture.

Introduction

In the last fifty years, Chemical fertilizers and pesticides have been essential in enhancing agricultural productivity by their quick action and low cost; however, toxic effects on the environment, plants, animals, and human being along with pest resistance, have brought back interest towards eco-friendly approaches. Consequently, Integrated Pest Management (IPM) has assumed great significance and biopesticides as important elements of IPM, although their availability on a large scale is a big constraint (1).

Received: October 25, 2025. Accepted: January 9, 2026. Published: March 12, 2026

The indiscriminate use of chemical pesticides has reduced soil productivity and increased soil salinity. Biofertilizers, consisting of beneficial microorganisms such as bacteria, fungi, and algae, offer a sustainable and economical alternative by improving nutrient availability through processes like nitrogen fixation and the solubilization of phosphorus and potassium (2).

The development of horticultural crops is confronted with numerous issues today. Some root factors contributing to the woes are the following: (i) the projected rise in the global population estimated to reach up to 10 billion by the year 2050, the demographic transforming to urban populations that are basically consumers but not producers of source foods (1-3), (ii) the accelerating negative influence from environmental factors such as the formation of salinity, drought, disease pressure, and toxicity by toxic heavy metals, all aggravated by alterations in the climate, thereby decreasing the supply of arable lands and damaging the yields from crops (4-9), increased efficiency in the utilization of resources to attempt to cap the environmental leakage from chemicals (10), as well as the amplified use of pesticides, among other fungicides, bactericides, herbicides, and other chemical reagents for biotics control, alongside the resultant environment as well as health concerns by their unabashed utilization (11). Biofertilizers are eco-friendly agricultural inputs that use living organisms such as bacteria and fungi to improve soil fertility and increase crop yield. They enhance nutrient availability through nitrogen fixation and phosphorus mobilization, reducing the need for chemical fertilizers and their negative environmental impacts. Studies and meta-analyses indicate that biofertilizers significantly improve nutrient use efficiency and crop productivity, especially in dryland agriculture. (12).

It is necessary to increase crop yields without greatly expanding the land, water, and fertilizer. From this viewpoint, the diversity of plant-associated and soil microorganisms is one of the most researched fields for the introduction and development of sustainable horticultural, agricultural, and forestry management systems. The utilization of endophytic microbes that trigger defense mechanisms and increase the growth of the endosphere-residing plants—without any undesirable effect—is considered an input-low, cheap, rapid, climate-smart, and environment-friendly biological means to an end to develop the adaptive potentiality and quality/yield of crops under the impact of changing environmental stimuli (13). Today, the presence of endophytic microorganisms is well-documented, and their potential application for crop improvement is getting more attention (14-16).

Management styles of agriculture are now directed towards a greater degree of environmental sustainability. Therefore, organic farming, as the EU and the FAO acknowledge, is a replacement for mainstream farming and appears to be a growing and environmentally sustainable system (17). Mineral fertilizer misuse and abuse lead to health problems and pollution of the environment (18). Organic farming is reputed to be the most rapidly developing form of agriculture in the world. Between 2001 and 2011, the overall global organic agricultural hectares (ha) increased by 135% (19), representing a compound growth of 8.9% annually for that ten-year period.

Global demand for organic tree fruit products, particularly in Europe and the United States/Canada, has driven significant growth in organic production areas between 2008 and 2013 of 109% in temperate fruit, 42% in citrus fruit, and 53% in tropical/subtropical fruits. Although organic tree fruits as a whole make up just 1–2% of the total area of production, avocado stands out with 8% organically cultivated worldwide. Mexico, Italy, and China lead the organic area of tree fruit, although reporting standards are different. Organic yields compared with conventional range extensively (42–126%), whereas the cost of production is generally higher, especially for fertilizer. Nevertheless, better market prices usually offset lower yields and increased costs with better net returns. Technological advances such as pheromone mating disruption have enabled this increase, with additional innovation required to control invasive pests, climate change, and the need for resistant cultivars and alternative pest management products (20).

Liquid organic fertilization relatively improved nutrient uptake, vegetative growth, storage of carbohydrates, and soil health of citrus trees compared to Mineral fertilization. Citrus trees supplied with animal-derived liquid fertilizer were found to have increased biomass, increased leaf and fibrous root development, more carbohydrate content in summer flush leaves, and improved soil organic matter. Animal-based fertilizer reduced soil nitrate contents while increasing available phosphorus and magnesium in comparison with plant-based fertilizer. Such observations suggest that liquid organic fertilizers, particularly those from animal sources, are a suitable alternative to conventional mineral fertilization of citrus groves under drip irrigation (21).

Foundational Concepts and Early Comparative Efficacy of Organic Systems

Research on organic systems and their comparative performance has elicited a great deal of interest in recent years, particularly within sustainable farming systems. The literature reveals that there is a complex interlink between the merits and problems associated with organic farming (22). provide a backdrop, noting that while the green revolution significantly increased global cereal yields, it had adverse effects on natural resources and hence catalyzed a system-oriented direction in agriculture. The system-oriented approaches emphasize sustainability, soil fertility, and reduced application of external inputs, and argue that well-managed organic systems can equal conventional systems in yields under optimum conditions. However, the authors also cite criticisms against organic farming, particularly on labor productivity and yield stability grounds, that challenge it meeting the world food demand.

Building on this foundation, (23) investigate the sophistication concerning the outcomes of organic agriculture more deeply, presenting it as a potential solution to sustainable food production. The authors highlight the benefits of organic systems, such as greater biodiversity and better soil, but also acknowledge the price of these, which is lower output and higher consumer prices. Authors suggest a more situational evaluation of organic farming, taking it beyond dyadic criticism regarding its efficacy to better understand the specific circumstances under which organic farming succeeds or fails. A critical perspective is warranted, for today, organic farming is found at the margins of agricultural land and food sales worldwide.

(24) Contribute to this discussion by synthesizing labor dynamics on organic farms. Their synthesis shows that organic agriculture is more labor-intensive than conventional agriculture, but this varies by region and crop type. The authors call for a greater understanding of labor utilization as an important variable in organic agriculture adoption and intensification as demand continues to rise.

The participatory model highlighted by (25) adds another layer to the discussion, with a focus on stakeholder involvement in alternative food systems. Their review of the literature demands holistic research that reflects both the potential and constraints of organic agriculture, in which one may find standards of production overriding social and environmental ideals.

The first evidence base for their application in horticulture originates from the first comparative long-term trials between organic and conventional systems. A groundbreaking 21-year experiment published in 2002 demonstrated that while organic farming systems achieved 20% lower yields than conventional agriculture, they reduced fertilizer and energy inputs ranging from 34% to 53%, while pesticide application decreased by 97%, accompanied by improvements in soil fertility and biodiversity (26). This early work highlighted the main trade-offs and benefits, a fact further supported through a 2005 review that found organic technologies promote higher organic content and nitrogen concentration in the soil, along with preserving soil moisture (27).

These systems' ideas about soil fertility were not conceived as inherently different from traditional ones, but as systems where the same nutrient cycling processes occur, but with relative differences and rates of significance (28).

Research at the time began to concentrate its studies more on tree crops, as demonstrated by a 2008 study that indicated that organic fertilizer treatments produced almonds with improved chemical quality containing increased amounts of sugar and organic acids (29) compared to using mineral fertilizers. Subsequent research in 2012 began to make a differentiation between organic inputs, which examined how, in turn, conventional manure, bio-organic fertilizer, or organic-inorganic compound fertilizers differently affect pear tree growth and fruit quality (30).

These early studies, for example, a 2006 review of biological choices of sustainable soil management in tree-crop agroforestry that elaborated on practices like soil fertility regulation using fertilizer trees and compost (31), as a group formed the scientific foundation for the investigation of organic and biological amendments to soil in perennial horticulture.

Olive oil production generates highly polluting wastewater containing large amounts of organic and inorganic compounds. In Tunisia, the application of olive mill wastewater (OMW) to soil has been adopted to manage this waste and enhance the organic matter in olive groves. Incubation of two types of artificial soil with 40 and 80 $m^3 \cdot ha^{-1}$ of OMW increased organic matter, phosphorus, nitrogen, and potassium contents. The adsorption of phenolic compounds depended on the type of clay, with notable effects in soils containing bentonite clay. The germination index of tomato and alfalfa seeds showed positive results when OMW was applied, indicating that this practice can serve as a waste management strategy, reduce the need for chemical fertilizers, and provide a carbon source for organic farming (32).

The only substantial problem facing current sustainable agriculture is the level of excessive and unnecessary fertilization, with no adverse effect on the nutritional need for plants or crop growth and product quality. In particular, excessive use of inorganic fertilizer has led to the deterioration of the soil by intensified salinification and acidification, also pollution of surface water and underground water, alongside intensified greenhouse gas emissions (33). Further still, the decline in microbial activity must hereby also be taken into consideration. The outrageous financial cost associated with the inorganic fertilizer, alongside the implications for the environment, makes the quest for alternative sources of nutrients an effort to reduce the utilization of the inorganic fertilizer (34).

Lastly, (35) gives a modern insight into the quality and nutritional character of food grown by organic systems. From their findings, it is noted that organic food tends to carry fewer dangerous substances while keeping or even surpassing beneficial nutrient levels than conventional food. Nevertheless, they also advise that organic farming is still a small substitute because of yield and cost problems. The authors encourage research for enhancing the sustainability and quality of organic production, particularly in the context of growing population pressure.

Rise of Biofertilizers: Mechanisms, Application, and Efficacy in Tree Crops

Taking strength from the established benefits of general organic systems, research between the period 2013-2020 turned towards the mechanism and applications of biofertilizers as effective, targeted alternatives to chemical inputs. This was the period that transitioned from bulk organic matter to microbial activity, driven by a quest to create good and sustainable bio-fertilizers to greatly reduce inorganic fertilizer use (1). A 2018 review mandated that bio-fertilizers contain microorganisms that ensure proper nutrient supply to host plants (36) and, therefore, play a fundamental part in preserving soil fertility and ensuring long-term sustainability.

The mechanisms of action of these bio-inoculants were well explained in a review published in 2021, and it further clarified that Plant Growth Promoting Rhizobacteria (PGPR) employ direct and indirect processes; direct mechanisms are improving plant nutrition through nitrogen fixation or mineral solubilization, and indirect effects are suppressing phytopathogens through the synthesis of inhibitory metabolites or the activation of systemic resistance (37).

Experiments during this time integrated such principles to tree fruits, and citrus grove experiments particularly focused on the integration of several biofertilizers, including nitrogen-fixing bacteria such as Azotobacter and Azospirillum, along with phosphate-solubilizing bacteria, including Bacillus and Pseudomonas (38).

Treatment with PGPR (including Azotobacter chroococcum, Bacillus megaterium, and Bacillus circulans) resulted in the highest levels of yield, nutrient content, and fruit quality compared to treatments with organic matter alone or the control (39).

Similarly, a Halabja pomegranate seedling trial demonstrated that Bacillus subtilis inoculation together with nano-iron sprays (40 mg L^{-1}) was optimal for maximizing growth, nutrient uptake, and carbohydrates (40).

Dry root rot (DRR) of citrus, which was mostly induced by Neocosmospora (Fusarium) solani, was controlled effectively using antagonist rhizobacteria that were isolated from the rhizosphere of citrus. Out of 210 tested isolates, 20 were isolated to nine species of Bacillus, Stenotrophomonas, and Sphingobacterium. Greenhouse experiments indicated that the Bacillus subtilis strains K4-4 and GH3-8 suppressed DRR in a complete manner, indicating their use as potential biocontrol agents and biofertilizers for sustainable citrus production (41).

Long-term fertilization promoted kiwifruit orchard yields by enriching rhizosphere microbial diversity and PGPR density in the rhizosphere (42). Strawberry growth was also improved through increased microbial community composition (43). Research showed that vermicompost improved the antioxidant and antimicrobial activities in C. cajan leaves and in farmyard manure improved phenol content and chlorophyll, and olive mill waste compost improved oil production in olive plantation (diverse sources).

In addition to nutrition, organic amendments also deliver ecosystem services. Agriculture is increasingly being recognized as not only food production but also an industry that generates ecosystem services, such as conservation tillage, crop diversification, organic fertilization, and improved soil organic C, fertility, and quality (44). This indicates the critical role of soil organic carbon in rendering all activities toward sustainable orchard management.

A long-term field trial (2009–2013) in Poland tested a range of bio-fertilizers on organically cultivated apple variety 'Ariwa', with Humus UP and Vinassa treatments enhancing growth, yield, and fruit quality

(45). Field and pot trials (2019–2020) on young olive trees have more recently confirmed that organic fertilizers with biostimulant activity significantly promoted vegetative and reproductive growth without sacrificing yield (46).

Organic fertilization is increasingly accepted as a sustainable alternative to inorganic fertilization in tree orchards to reduce chemical inputs, save the environment, and enhance fruit quality (15). Furthermore, synergistic inoculations (e.g., Frankia + VAM, Rhizobium + VAM) have been shown to enhance nitrogen fixation and biomass of trees such as Casuarina and Acacia (23).

Advanced and Integrated Approaches: Synergistic Effects and Modern Innovations

The newest research wave, started in 2021, has focused on the creation of synergistic effects through combining numerous organic and biological components, in addition to knowing individual-application inputs. This is a recurring theme of new mixes, since a 2023 study found that incorporating organic by-products such as compost, biochar, and anaerobic digestate promoted plant growth more effectively than taking a single product in isolation (47), maybe by stimulating a more active soil microbiome. The time also grapples with the issue of translating laboratory success into field applications, as a 2021 review noted that a highly performing microbial strain in vitro often performs badly in field trials (48) due to a variety of uncontrolled abiotic and biotic factors.

These new advances—microbial endophytes, nanomaterials, strigolactones, CRISPR-mediated breeding, and controlled environment agriculture with artificial lighting—pose high potential for increasing plant growth, yield, stress tolerance, and resource use efficiency. These approaches increase metabolic, morphological, and biochemical traits of crops that result in higher productivity and quality in the field and greenhouse (49).

These integrated approaches have been applied in recent work for tree health, such as in a 2021 study demonstrating that bacterial isolates like Bacillus subtilis could completely suppress dry root rot disease in greenhouse tests on citrus (41). Inoculation of apple trees with arbuscular mycorrhizal fungi (AMF) and PGPR was reported in another study in 2021 to enhance the trunk cross-section area by 24% and the leaf nitrogen and magnesium concentration (50).

Factorial randomized complete block design was utilized to evaluate soil chemical fertilizer (CF) at three rates (100%, 75%, and 50% of the normal dose) plus foliar NPK (20-20-20 + micronutrients) and biological fertilizer (BF) at three rates: control (BF0), soil-applied organic blend (BF1) with mycorrhizal fungi, Bacillus subtilis, Pseudomonas fluorescens, along with fulvic acid, amino acids, and the BF1+BFF combination with soil and foliar sprays of the same ingredients (51).

A field experiment carried out in 2023 in northern Dohuk, Iraq, assessed the influence of foliar applications of arginine, melatonin, and nano-chelated Zn–Fe on apricot (Prunus armeniaca) trees, utilizing a randomized complete block design with three replications. Among the 28 treatment combinations tested, the combination of arginine (150 ppm), melatonin (400 μmol L^{-1}), and Zn–Fe nano-chelate (2–3 g L^{-1}) yielded the most significant enhancements in yield and various fruit quality parameters, such as fruit firmness, weight, length, vitamin C content, soluble sugars, and mineral concentrations (Ca, Mg, K, Zn, Fe), while simultaneously lowering acidity and improving leaf chlorophyll levels and leaf area. The findings of the study suggest that these particular combinations should be recommended to enhance both quantitative and qualitative outcomes in apricot production under comparable conditions (40).

One-year-old pomegranate (Halabja variety) transplants were tested in a trial at the Lath-house, College of Agricultural Technology, Northern Technical University. Bacillus subtilis inoculation into soil and nano-iron sprays at 0, 20, and 40 mg L^{-1} were tested in the experiment. Plant growth was enhanced by an increase in stem height and thickness, branching pattern, and number of leaves, as well as fresh and dry weight. The best growth performance was obtained when B. subtilis was combined with the highest nano-iron concentration (40 mg L^{-1}) (52).

Whereas organic fertilization is capable of improving yields together with the quality of the onsite crop, coupled with the expanding consumer requirements for certified organic (biological) crop (53), the quality organic fruit emphasis is forecast to intensify over the next few years by way of potential markets, where the monetary payment for the certified organic fruits will be potentially higher.

Foliar application with biological fertilizers, even at low rates, considerably enhanced the antioxidant leaf and fruit contents. Studies on different olive varieties grown in calcareous soils have been reported by (4). Increasing the antioxidant levels in olive fruits is vital for human nutrition and health. Foliar treatments with biofertilizers have been demonstrated by (54) to improve both quantitative and qualitative fruit traits.

Further, (55) researched mature olive crops and determined that the usage of a liquid organic product made up of humic and fulvic acid by folio-dropping had significantly impacted oil yields as well as fruiting considerably, under alkaline conditions. Use of folio-drops made up of amino acids alongside the application of the fullvic acid supports the extensive remobilization of nutrients by the above-ground plant tissue with their uptake, thus the optimal growth of the crop (56). Certain amino acids, such as cysteine and phenylalanine, activate the metabolism of antioxidant molecules as well as resistance enzyme activity upon their application by folio-dropping (57). Folio-dropping by amino acids alongside biofertilizers such as Bacillus amyloliquefaciens has been cultivated to raise crop productivity. The application by the symbiotic microorganisms may also modify the composition of the leaf's microbiota, thus enhancing the health of the crop (58). Apparently, the synergistic action between the amino acids, as well as plant growth-stimulating bacteria, had the potential to considerably raise the crop yield as well as the development rate by roots (59).

Mineral fertilization, although required for crop cultivation, exerts an adverse effect on certain soil properties in monocropping systems, particularly in relation to soil pH and humus status. The integration of mineral and organic fertilizers reduces these adverse effects and improves soil fertility through the enhancement of its physical, chemical, and biological characteristics. Humus active substances can also stimulate seed germination, plant growth, nutrient uptake, and protein metabolism. Long-term trials confirm that combined fertilization increases yields by approximately 10% in sandy soils and 6% in clay soils (60- 62).

There has been a fairly good measure of evidence to demonstrate that organic fertilization has a positive effect on growth and field productivity in trees (42,53,63-66), thereby highlighting the positive role of organic soil mulches in enhancing tree biomass and yields, presumably owing to improved soil fertility and nutrient content in plants. Indeed, a majority of the evidence that has been documented indicates that levels of foliar nutrient content and nutrient uptake achieved as a consequence of organic fertilization are equal to or equivalent to those achieved as a consequence of inorganic (traditional) fertilization (44, 67), and still more positive effects are found to be documented when it comes to utilizing organic options (68,69). Taking into account that nutrient supply falls among the important determiners that influence plant growth and productivity, as well as water, temperature, and solar radiation (70), it therefore stands to reason that under equivalent environmental determiners, equal or higher-than-equal levels of plant nutrition utilizing organic fertilizers, in comparison to inorganic ones, are feasible, thereby translating to equal or higher-than-equal plant biomass and tree productivity.

Comparative studies related to intensive conventional mono-cropping of fruit orchards, as well as crop diversification, conservation tillage, and use of organic fertilizers, found that tree crops' yields did not vary due to fertilization in an organic manner (71). This finding shows that it has the same beneficial effects on tree productivity as the inorganic version.

A project supported by the EU compared innovative methods of organic nursery production of apple maiden trees ('Topaz' and 'Ariwa' on M26 rootstocks). Treatments consisted of a vegetal amino-acid fertilizer (BF Amin), mycorrhizal fungi and PGPR consortia (Micosat F12WP and Micosat FMS 200), organic animal manure (NPK), and a non-fertilized control. BF Amin significantly improved branching, lateral shoot development, tree height, and trunk thickness in both cultivars, while Micosat also improved branching but less impressively. The aforementioned results suggest that BF Amin and Micosat can be used effectively in organic apple nurseries to improve the quality of trees (72).

Research Gaps & Future Directions

Theme 1 – Foundational research

Foundational research often compared entire organic systems against conventional ones, leaving a gap in isolating the effects of specific organic fertilizer types on tree health. It also did not fully explore strategies to close the identified yield gaps for perennial crops.

Theme 2 – Biofertilizers

In the subsequent period focusing on biofertilizers, a significant gap emerged between the success of microbial inoculants in controlled lab settings and their inconsistent field performance, as noted in comprehensive reviews on PGPR (5). There is a clear need for research to identify the specific orchard soil and environmental factors that limit or enhance their efficacy.

Theme 3 – Integrated approaches

Recent work on integrated approaches has shown synergistic benefits but has primarily focused on annual crops. A major gap exists in applying these multi-component organic fertilizers to long-term tree orchard systems to assess their impact on health, yield, and soil carbon over several years (47). Furthermore, the economic scalability of these advanced formulations for commercial orchardists remains underexplored.

Cross-theme opportunity

A significant cross-theme opportunity lies in conducting long-term field trials on tree crops that directly compare advanced, synergistic fertilizers from Theme 3 against the single-source organic inputs of Theme 1 and the specific bio-inoculants of Theme 2. A testable hypothesis is that a combined application of compost, biochar, and a PGPR/AMF consortium will outperform any single treatment in improving tree nutrient status, disease resistance, and fruit yield, thereby addressing the yield gap noted in early research.

Nitrogen management in orchards

Effective nitrogen (N) management in fruit tree orchards means synchronizing fertilization with the nutrient requirements of trees, irrigation planning, and pruning to optimize the relationship between growth and flowering. This decreases fertilizer N use inefficiently and lessens N losses from the system. Besides, the growing market demand for organic fruits makes the application of sustainable practices like mulching, cover crops, and legumes for biological N_2 fixation that contribute toward the growth of soil organic N, as well as increasing sustainability under climate change adaptation strategies (73).

Concluding remarks

In a nutshell, application of organic fertilizers has several virtues to agroecosystems, such as enhancing soil physical characteristics and fertility, enhancing soil microbial activity, and enhancing general soil condition. Nonetheless, a major drawback is that it cannot rapidly meet the nitrogen nutritional requirement of crops since the process of mineralization, which is typical of nitrogen present in organic form, is slow. This drawback can, nonetheless, be offset through integrated methods of fertilization, which include the application of both organic and nitrogenous fertilizers.

Concerning the influence of organic fertilization on the productivity of tree crops, the vast majority of researchers have reported similar biomass, yield, and productivity compared with that from inorganic fertilization. Furthermore, new organic fertilizers, particularly those that contain beneficial added microorganisms, have recently been demonstrated to improve fruit quality, arguably due to the rise in soil microbial populations and functions. Common organic and biological sources to tree crops include organic manures together with olive mill by-products (OMW), agricultural residues, treated sewage sludge, compost materials, shredded pruning residues, and green cover crops. Results are more than promising according to numerous studies.

It is therefore anticipated that, in the not-so-distant future, new organic fertilizers (especially those with incorporated beneficial microorganisms) will be significant in sustaining, and even expanding, orchard yields. At the same time, they will meet the healthier, improved quality fruit production needs of society, as well as a healthy environment through reduced consumption of inorganic fertilizers and improved ecosystem services within orchard systems.

Conflict of interest: NIL

Funding: NIL

References

1. Aggani, S. (2013). Development of bio-fertilizers and its future perspective. *Scholars Academic Journal of Pharmacy*. https://www.saspublishers.com/media/articles/SAJP24327-332.pdf
2. Chaâri, L., Alsaiari, N. S., Amari, A., Ben Rebah, F., Kallel, M., & Mechichi, T. (2022). Soil Responses to High Olive Mill Wastewater Spreading. *Agronomy*, *12*(4), 972. https://doi.org/10.3390/agronomy12040972
3. Kumar, M. P. S., Reddy, G. C., Phogat, M., & Korav, S. (2018). Role of bio-fertilizers towards sustainable agricultural development: A review. *Journal of Pharmacognosy and Phytochemistry*. https://www.semanticscholar.org/paper/be6a550b7892b581cf44867a12466138cbe35685
4. Maksoud, M. A., Saleh, M. A., El-Shamma, M. S., and Fouad, A. A. (2009). The beneficial effect of biofertilizers and antioxidants on olive trees under calcareous soil conditions. World J. Agric. Sci. 5, 350–352.
5. Basu, A., Prasad, P., Das, S. N., Kalam, S. N., Sayyed, R., Reddy, M., & Enshasy, H. E. (2021). Plant Growth Promoting Rhizobacteria (PGPR) as Green Bioinoculants: Recent Developments, Constraints, and Prospects. *Sustainability*. https://www.mdpi.com/2071-1050/13/3/1140
6. Kozai, T.; Niu, G.; Takagaki, M. *Plant Factory: An Indoor Vertical Farming System for Efficient Quality Food Production*, 2nd ed.; Elsevier Academic Press: San Diego, CA, USA, 2019; p. 516.
7. Shomali, A.; Aliniaeifard, S. Overview of signal transduction in plants under salt and drought stresses. Salt and drought stress tolerance in plants. In *Signaling Networks and Adaptive Mechanisms*; Hasanuzzaman, M., Tanveer, M.,

Eds.; Springer International Publishing: Cham, Switzerland, 2020; pp. 231–258.

8. Sarraf, M.; Vishwakarma, K.; Kumar, V.; Arif, N.; Das, S.; Johnson, R.; Janeeshma, E.; Puthur, J.T.; Aliniaeifard, S.; Chauhan, D.K. Metal/metalloid-based nanomaterials for plant abiotic stress tolerance: An overview of the mechanisms. *Plants* **2022**, *11*, 316.
9. Seifikalhor, M.; Niknam, V.; Aliniaeifard, S.; Didaran, F.; Tsaniklidis, G.; Fanourakis, D.; Teymoorzadeh, M.; Mousavi, S.H.; Bosacchi, M.; Li, T. The regulatory role of γ-Aminobutyric acid in chickpea plants depends on drought tolerance and water scarcity level. *Sci. Rep.* **2022**, *12*, 1–17.
10. Tian, H.; Lu, C.; Pan, S.; Yang, J.; Miao, R.; Ren, W.; Yu, Q.; Fu, B.; Jin, F.-F.; Lu, Y. Optimizing resource use efficiencies in the food–energy–water nexus for sustainable agriculture: From conceptual model to decision support system. *Curr. Opin. Environ. Sustain.* **2018**, *33*, 104–113.
11. Rani, L.; Thapa, K.; Kanojia, N.; Sharma, N.; Singh, S.; Grewal, A.S.; Srivastav, A.L.; Kaushal, J. An extensive review on the consequences of chemical pesticides on human health and environment. *J. Clean. Prod.* **2021**, *283*, 124657.
12. Mustafa, M. N., & Al-Abbasi, A. T. (2025). Biofertilizers as Eco-Friendly Alternatives in Fruit Cultivation for Sustainable Development-Review.
13. Glick, B.R.; Gamalero, E. Recent developments in the study of plant microbiomes. *Microorganisms* **2021**, *9*, 1533.
14. Glick, B.R.; Gamalero, E. Recent developments in the study of plant microbiomes. *Microorganisms* **2021**, *9*, 1533.
15. Hardoim, P.R.; van Overbeek, L.S.; Berg, G.; Pirttilä, A.M.; Compant, S.; Campisano, A.; Döring, M.; Sessitsch, A. The hidden world within plants: Ecological and evolutionary considerations for defining functioning of microbial endophytes. *Microbiol. Mol. Biol. Rev.* **2015**, *79*, 293–320.
16. Compant, S.; Cambon, M.C.; Vacher, C.; Mitter, B.; Samad, A.; Sessitsch, A. The plant endosphere world–bacterial life within plants. *Environ. Microbiol.* **2021**, *23*, 1812–1829.
17. Polat E, Demiri H, Erler F. Yield and quality criteria in organically and conventionally grown tomatoes in Turkey. Sci Agricola 2010; 67(4): 424–429. doi: 10.1590/S0103901620100000400008
18. Zahoor WA, Khanzada H, Bashir U., Aziz K, Zahir S, Faheem AK, et al. Role of Nitrogen Fertilizer in Crop Productivity and Environmental Pollution. Int J Agric For. 2014; 4(3): 201–206 doi: 10.5923/j.ijaf. 20140403.09
19. Willer H, Kilcher L In The World of Organic Agriculture: Statistics and Emerging Trends. Bonn: International Federation of Organic Agriculture Movements (IFOAM); Frick, Switzerland: Research Institute of Organic Agriculture (FiBL). 2011.
20. Granatstein, D., Kirby, E., Ostenson, H., & Willer, H. (2016). Global situation for organic tree fruits. *Scientia Horticulturae*, *208*, 3–12. https://doi.org/https://doi.org/10.1016/j.scienta.2015.12.008
21. Martínez-Alcántara, B., Martínez-Cuenca, M.-R., Bermejo, A., Legaz, F., & Quiñones, A. (2016). Liquid Organic Fertilizers for Sustainable Agriculture: Nutrient Uptake of Organic versus Mineral Fertilizers in Citrus Trees. *PLOS ONE*, *11*(10), 1–20. https://doi.org/10.1371/journal.pone.0161619
22. Forster, D., Andres, C., Verma, R., Zundel, C., M. Messmer, M., & Mäder, P. (2013). Yield and Economic Performance of Organic and Conventional Cotton-Based Farming Systems – Results from a Field Trial in India. ncbi.nlm.nih.gov
23. Seufert, V. & Ramankutty, N. (2017). Many shades of gray—The context-dependent

performance of organic agriculture. ncbi.nlm.nih.gov

24. Orsini, S., Padel, S., & Lampkin, N. (2018). Labour Use on Organic Farms: A Review of Research since 2000. [PDF]
25. Sacchi, G., Cei, L., Stefani, G., Lombardi, G., Rocchi, B., Belletti, G., Padel, S., Sellars, A., Gagliardi, E., Nocella, G., Cardey, S., Mikkola, M., Ala-Karvia, U., Macken-Walsh, \uc0ine, McIntyre, B., Hyland, J., Henchion, M., Bocci, R., Bussi, B., De Santis, G., Rodriguez y Hurtado, I., de Kochko, P., Riviere, P., Carrascosa-Garc\ueda, M., Mart\uednez, I., Pearce, B., Lampkin, N., Vindras, C., Rey, F., Chable, V., Cormery, A., & Vasvari, G. (2018). A Multi-Actor Literature Review on Alternative and Sustainable Food Systems for the Promotion of Cereal Biodiversity. [PDF]
26. Maeder, P., Fliessbach, A., Dubois, D., Gunst, L., Fried, P., & Niggli, U. (2002). Soil Fertility and Biodiversity in Organic Farming. *Science*. https://www.science.org/doi/10.1126/science.1071148
27. Pimentel, D., Hepperly, P., Hanson, J., Douds, D., & Seidel, R. (2005). *Environmental, Energetic, and Economic Comparisons of Organic and Conventional Farming Systems*. https://academic.oup.com/bioscience/article/55/7/573-582/306755
28. Stockdale, E., Shepherd, M., Fortune, S., & Cuttle, S. (2002). Soil fertility in organic farming systems fundamentally different? *Soil Use and Management*. https://bsssjournals.onlinelibrary.wiley.com/doi/10.1111/j.1475-2743.2002.tb00272.x
29. Sánchez-Bel, P., Egea, I., Martínez-Madrid, M. C., Pardo, F., & Romojaro, F. (2008). Influence of Irrigation and Organic/Inorganic Fertilization on Chemical Quality of Almond (*Prunus amygdalus* cv. Guara). *Journal of Agricultural and Food Chemistry*. https://doi.org/10.1021/jf8012212
30. Song, X., Xie, K., Zhao, H., & Li, Y. (2012). *Effects of different organic fertilizers on tree growth, yield, fruit quality, and soil microorganisms in a pear orchard*. https://www.cabidigitallibrary.org/doi/pdf/10.1079/ejhs.2012/3477618
31. Uphoff, N. (2006). *Biological Approaches to Sustainable Soil Systems*. https://www.taylorfrancis.com/books/9781420017113
32. Chaâri, L., Alsaiari, N. S., Amari, A., Ben Rebah, F., Kallel, M., & Mechichi, T. (2022). Soil Responses to High Olive Mill Wastewater Spreading. *Agronomy*, *12*(4), 972. https://doi.org/10.3390/agronomy12040972
33. Miao, Y.; Stewart, B.A.; Zhang, F. Long-term experiments for sustainable nutrient management in China. A review. *Agron. Sustain. Dev.* **2011**, *31*, 397–414.
34. Jakubus, M.; Bakinowsk, E. Visualization of long-term quantitative changes of microelements in soils amended with sewage sludge compost evaluated with two extraction solutions. *Commun. Soil Sci. Plant Anal.* **2018**, *49*, 1355–1369.
35. Çakmakçı, S. & Çakmakçı, R. (2023). Quality and Nutritional Parameters of Food in Agri-Food Production Systems.
36. Kumar, M. P. S., Reddy, G. C., Phogat, M., & Korav, S. (2018). Role of bio-fertilizers towards sustainable agricultural development: A review. *Journal of Pharmacognosy and Phytochemistry*. https://www.semanticscholar.org/paper/be6a550b7892b581cf44867a12466138cbe35685
37. Basu, A., Prasad, P., Das, S. N., Kalam, S. N., Sayyed, R., Reddy, M., & Enshasy, H. E. (2021). Plant Growth Promoting Rhizobacteria (PGPR) as Green Bioinoculants: Recent Developments, Constraints, and Prospects. *Sustainability*. https://www.mdpi.com/2071-1050/13/3/1140
38. Abobatta, W. F., & El-Azazy, A. M. (2020). Role of organic and biofertilizers in citrus orchards. *Aswan University Journal of Environmental*

Studies. https://doi.org/10.21608/aujes.2020.124530

39. El-Razek, E. A., Haggag, L. F., El-Hady, E. S., & Shahin, M. F. M. (2020). Effect of soil application of humic acid and bio-humic on yield and fruit quality of "Kalamata" olive trees. *Bulletin of the National Research Centre/Bulletin of the National Research Center*. https://doi.org/10.1186/s42269-020-00318-8
40. Ali AL-Qady, R. A., W. W. Ahmad, W. S. Faizy, M. N. Mustafa, B. Yousefi, and H. Meftahizade. 2025. " Unveiling the Synergistic Effects of Melatonin, Arginine, and Nano-Chelated Zn-Fe on Enhancing Fruit Quality in Apricot (*Prunus armeniaca*)." *Food Science & Nutrition* 13, no. 7: e70559. https://doi.org/10.1002/fsn3.70559.
41. Ezrari, S., Mhidra, O., Radouane, N., Tahiri, A., Polizzi, G., Lazraq, A., & Lahlali, R. (2021). Potential Role of Rhizobacteria Isolated from Citrus Rhizosphere for Biological Control of Citrus Dry Root Rot. *Plants*, *10*(5), 872. https://doi.org/10.3390/plants10050872
42. Liu, Z.; Guo, Q.; Feng, Z.; Liu, Z.; Li, H.; Sun, Y.; Liu, C.; Lai, H. Long-term organic fertilization improves the productivity of kiwifruit (*Actinidia chinensis* Planch.) through increasing rhizosphere microbial diversity and network complexity. *Appl. Soil Ecol.* **2020**, *147*, 103426.
43. Zhang, J.; Pang, H.; Ma, M.; Bu, Y.; Shao, W.; Huang, W.; Ji, Q.; Yao, Y. An apple fruit fermentation (AFF) treatment improves the composition of the rhizosphere microbial community and growth of strawberry (*Fragaria* x *ananassa* Duch 'Benihoppe') seedlings. *PLoS ONE* **2016**, *18*, e0164776.
44. Garcia-Orenes, F.; Roldan, A.; Morugan-Coronado, A.; Linares, C.; Cerda, A.; Caravaca, F. Organic fertilization in traditional Mediterranean grapevine orchards mediates changes in soil microbial community structure and enhances soil fertility. *Land Degrad. Dev.* **2016**, *27*, 1622–1628.
45. Rozpara, E., Pąśko, M., Bielicki, P., & Sas Paszt, L. (2013). Influence of several organic fertilizers on growth, yield, and fruit quality of organically grown apple cultivar 'Ariwa' in Poland. *Institute of Horticulture, Skierniewice, Poland*.
46. Mazeh, M., Almadi, L., Paoletti, A., Cinosi, N., Daher, E., Tucci, M., Lodolini, E. M., Rosati, A., & Famiani, F. (2021). Use of an Organic Fertilizer Also Having a Biostimulant Action to Promote the Growth of Young Olive Trees. *Agriculture*, *11*(7), 593. https://doi.org/10.3390/agriculture11070593
47. Ortiz-Liébana, N., Crespo-Barreiro, A., Mazuecos-Aguilera, I., & González-Andrés, F. (2023). Improved Organic Fertilisers Made from Combinations of Compost, Biochar, and Anaerobic Digestate: Evaluation of Maize Growth and Soil Metrics. *Agriculture*. https://www.mdpi.com/2077-0472/13/8/1557
48. Mitter, E., Tosi, M., Obregón, D., Dunfield, K., & Germida, J. (2021). Rethinking Crop Nutrition in Times of Modern Microbiology: Innovative Biofertilizer Technologies. *Frontiers in Sustainable Food Systems*. https://www.frontiersin.org/articles/10.3389/fsufs.2021.606815/full
49. Lastochkina, O., Aliniaeifard, S., SeifiKalhor, M., Bosacchi, M., Maslennikova, D., & Lubyanova, A. (2022). Novel Approaches for Sustainable Horticultural Crop Production: Advances and Prospects. *Horticulturae*, *8*(10), 910. https://doi.org/10.3390/horticulturae8100910
50. Przybyłko, S., Kowalczyk, W., & Wrona, D. (2021). The Effect of Mycorrhizal Fungi and PGPR on Tree Nutritional Status and Growth in Organic Apple Production. *Agronomy*. https://doi.org/10.3390/agronomy11071402
51. Tadayon, M. S., Asgharzadeh, A., Mousavi, S. M., & Sagha, K. (2025). *Synergistic effects of chemical and biochemical fertilization on yield*

enhancement and oil quality optimization in ' Zard ' olive cultivars. January. https://doi.org/10.3389/fpls.2025.1455921

52. Alalaf, Ayad. (2025). Efficiency of Biofertilization and Spraying Nano-Iron on Some Mineral Content and Carbohydrates in Leaves of Pomegranate Transplants CVS. Halabja. The future of Horticulture. 10.37229/fsa.fjh.2025.04.23.
53. Leonel, S.; Tecchio, M.A. Cattle manure fertilization increases fig yield. *Sci. Agric.* **2009**, *66*, 806–811.
54. Dabbaghi, O., Tekaya, M., M'barki, N., Ouled, A. S., Öden, S., Mezghani, M. A., et al.(2018). Effect of foliar bio-fertilization on growth and biochemical parameters of olive trees at flowering. J. Plant Nutr. 41, 2281–2297. Doi:10.1080/01904167.2018.1500592
55. Sotiropoulos, S., Chatzissavvidis, C., Papadakis, I. E., Kavvadias, V., Paschalidis, C., Antonopoulou, C., et al. (2024). Enhancing the yield of mature olive trees via comparative fertilization strategies, including a foliar application with fulvic and humic acids, in non-irrigated orchards with calcareous and non-calcareous soils.Horticulturae 10, 167. doi:10.3390/horticulturae10020167
56. Han, Ş., Sönmez, İ., Qureshi, M., Güden, B., Gangurde, S. S., and Yol, E. (2024). The effects of foliar amino acid and Zn applications on agronomic traits and Zn biofortification in soybean (Glycine max L.). Front. Plant Sci. 15. doi:10.3389/fpls.2024.1382397
57. Trovato, M., Funck, D., Forlani, G., Okumoto, S., and Amir, R. (2021). Amino acids in plants: Regulation and functions in development and stress defense. Front. Plant Sci.12. doi:0.3389/fpls.2021.772810
58. Wang, D., Deng, X., Wang, B., Zhang, N., Zhu, C., Jiao, Z., et al. (2019). Effects of foliar application of amino acid liquid fertilizers, with or without Bacillus amyloliquefaciens SQR9, on cowpea yield and leaf microbiota. PloS One 14,e0222048. doi: 10.1371/journal.pone.0222048
59. Freitas, J., and Silva, P. (2022). Sustainable agricultural systems for fruit orchards: The influence of plant growth promoting bacteria on the soil biodiversity and nutrient management. Sustainability 14, 13952. doi: 10.3390/su142113952
60. Bot A. Benites J. 2005. The importance of soil organic matter - Key to drought-resistant soil and sustained food and production. FAO soils bulletin. ISBN 92-5-105366-9.
61. Flaig W. 1968. Einwirkung von organischen Bodenbestandteilen auf das Pflanzenwachstum. Landwirtsch. Forsch., XXI, 2, 103-127.
62. Ouni Y., Ghnaya T., Montemurro F., Abdelly Ch., Lakhdar A. 2014. The role of humic substances in mitigating the harmful effects of soil salinity and improve plant productivity. International Journal of Plant Production, 8 (3), 353-374.
63. Jindo, K.; Chocano, C.; Melgares de Aguilar, J.; Gonzalez, D.; Hernandez, T.; Garcia, C. Impact of compost application during 5 years on crop production, soil microbial activity, carbon fraction and humification process. *Commun. Soil Sci. Plant Anal.* **2016**, *47*, 1907–1919.
64. Marron, N. Agronomic and environmental effects of land application of residues in short-rotation tree plantations: A literature review. *Biomass Bioenergy* **2015**, *81*, 378–400.
65. Kiczorowski, P.; Kopacki, M.; Kiczorowska, B. The response of Šampion trees growing on different rootstocks to applied organic mulches and mycorrhizal substrate in the orchard. *Sci. Hortic.* **2018**, *241*, 267–274.
66. Soudani, L.; Maatoug, M.; Heilmeier, H.; Kharytonov, M.; Wiche, O.; Moschner, C.; Onyshchenkoc, E.; Bouchenafa, N. Fertilization value of municipal sewage sludge for *Eucalyptus camaldulensis* plants. *Biotech. Rep.* **2017**, *13*, 8–12.

67. Chatzistathis, T.; Papadakis, I.E.; Papaioannou, A.; Chatzissavvidis, C.; Giannakoula, A. Comparative study effects between manure application and a controlled release fertilizer on the growth, nutrient uptake, photosystem II activity and photosynthetic rate of *Olea europaea* L. (cv. 'Koroneiki'). *Sci. Hortic.* **2020**, *264*, 109176.
68. Cai, A.; Xu, M.; Wang, B.; Zhang, W.; Liang, G.; Hou, E.; Luo, Y. Manure acts as a better fertilizer for increasing crop yields than synthetic fertilizer does by improving soil fertility. *Soil Tillage Res.* **2019**, *189*, 168–175.
69. Al-Ghumaiz, N.S.; Motawei, M.I.; Abd-Elmoniem, E.M.; Al-Otayk, S.M. Selenium and zinc concentrations in spring wheat (*Triticum aestivum*) genotypes under organic and inorganic fertilization. *J. Plant Nutr.* **2020**, *43*, 1980–1987.
70. Chatzistathis, T.; Therios, I. How Soil Nutrient Availability Influences Plant Biomass and How Biomass Stimulation Alleviates Heavy Metal Toxicity in Soils: The Cases of Nutrient Use Efficient Genotypes and Phytoremediators, Respectively. In *Biomass Now—Cultivation and Utilization*; Matovic, M.D., Ed.; IntechOpen: Rijeka, Croatia, 2013; Chapter 18; pp. 427–448.
71. Morugan-Coronado, A.; Linares, C.; Gomez-Lopez, M.D.; Faz, A.; Zornoza, R. The impact of intercropping, tillage and fertilizer type on soil and crop yield in fruit orchards under Mediterranean conditions: A meta-analysis of field studies. Agric. Syst. 2020,178, 102736. [CrossRef]
72. Grzyb, Z. S.; Piotrowski, W.; Bielicki, P.; Sas Paszt, L.; Malusà, E. (2012). *Effect of different fertilizers and amendments on the growth of apple and sour cherry rootstocks in an organic nursery*. Journal of Fruit and Ornamental Plant Research, 20(1), 43-53.
73. Carranca, C., Brunetto, G., & Tagliavini, M. (2018). Nitrogen Nutrition of Fruit Trees to Reconcile Productivity and Environmental Concerns. *Plants*, *7*(1), 4. https://doi.org/10.3390/plants7010004