

Plant Biostimulants In Pistachio (*Pistacia Vera L.*) Nursery and Orchard Systems: Evidence, Mechanisms and Research Priorities for Climate-Resilient Production

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Abstract

Pistachio (Pistacia vera L.) is adapted to dry environments, yet nursery plants and bearing orchards remain vulnerable to drought, salinity, heat, nutrient imbalance and disease pressure. Plant biostimulants are increasingly proposed to improve nutrient-use efficiency and stress tolerance, but evidence varies among product classes and experimental settings. This critical review evaluates direct evidence from pistachio and distinguishes it from mechanistic inference derived from other crops. Arbuscular mycorrhizal fungi (AMF) provide the most consistent pistachio-specific evidence. Controlled studies report improvements in biomass, mineral acquisition, water relations, photosynthetic performance, ion homeostasis and antioxidant regulation under drought or salinity, although responses depend on rootstock and stress intensity. Indigenous plant growth-promoting rhizobacteria (PGPR) also improve physiological traits under saline and water-limited conditions, but strain persistence and field reproducibility remain uncertain. Foliar Ascophyllum nodosum extract and fulvic acid have produced promising orchard-level biochemical and nutritional responses, whereas robust multi-year evidence for yield stability, nut quality and disease suppression remains limited. Regional research in Uzbekistan has confirmed Septoria pistaciae in pistachio, demonstrating that disease pressure is relevant to local production systems; however, pathogen occurrence should not be conflated with evidence of biostimulant-mediated control. Future research should use characterized products, rootstock-aware designs and multi-stress trials that measure physiological mechanisms alongside seedling survival, disease incidence and severity, marketable yield and economic return. Biostimulants should be treated as context-dependent components of integrated water, nutrient, soil and plant-health management rather than stand-alone substitutes for established agronomic and disease-management practices.

Keywords: Pistacia vera; arbuscular mycorrhizal fungi; PGPR; seaweed extract; fulvic acid; drought; salinity; disease monitoring; nursery; orchard resilience.

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1. Introduction

Pistachio is valued for its ability to remain productive under environmental conditions that exclude many other perennial crops. That adaptation, however, should not be interpreted as immunity to stress. Young plants are

especially sensitive during establishment, and drought or salinity can restrict root development, gas exchange, mineral acquisition and canopy growth. In mature orchards, these pressures interact with rootstock, crop load, soil heterogeneity and management history.

Consequently, a treatment that improves a physiological marker in a short greenhouse experiment cannot automatically be expected to increase seedling survival or marketable yield under field conditions.

Plant biostimulants have attracted attention because they can stimulate plant nutrition processes or stress responses without acting simply as conventional nutrient inputs. A widely used scientific definition is functional rather than ingredient-based: a biostimulant is a substance or microorganism that stimulates plant nutrition processes independently of its nutrient content, with the aim of improving nutrient-use efficiency, tolerance to abiotic stress, quality traits or nutrient availability in the rhizosphere (du Jardin, 2015; European Parliament and Council, 2019). This framing includes microbial inoculants such as AMF and PGPR and selected non-microbial products such as seaweed extracts and humic or fulvic fractions. It does not mean that every growth-promoting input, synthetic hormone, fertilizer or microbial antagonist is automatically a biostimulant.

This distinction is important for pistachio because the literature mixes several objectives: improved growth, drought or salt tolerance, nutritional stimulation, and suppression of plant pathogens. These outcomes are biologically related but are not equivalent. A larger root system may improve tolerance to environmental stress without directly suppressing a pathogen; conversely, an antagonistic microorganism may reduce disease without functioning primarily as a biostimulant. Internationally credible synthesis therefore requires claims to be matched to the type of evidence actually measured.

Biotic pressure also deserves explicit attention. In Uzbekistan, Nazarova et al. (2023) described the biological characteristics of *Septoria pistaciae* associated with pistachio. This regional evidence is relevant because pathogen pressure can influence canopy function, seedling quality and stress biomarkers. The study does not, however, demonstrate biostimulant efficacy. Its proper role in the present review is to establish disease relevance and to justify inclusion of disease incidence and severity as endpoints in future biostimulant experiments.

The objectives of this review are therefore to (i) identify

what has been demonstrated directly in *Pistacia vera* or pistachio rootstocks; (ii) distinguish direct evidence from mechanisms inferred from other crops; (iii) assess the extent to which current evidence supports claims about growth, abiotic-stress tolerance and disease resistance; and (iv) define research priorities relevant to nursery, orchard and dryland production systems, with particular attention to Central Asian conditions.

2. Review Approach and Evidential Boundaries

A structured narrative approach was used for the pistachio-focused evidence set. The underlying literature search, completed on 23 July 2026, used publisher platforms, PubMed, AGRIS and DOI-based searches with combinations of the terms *Pistacia vera*, pistachio, biostimulant, mycorrhiza, PGPR, rhizobacteria, seaweed extract, humic, fulvic, compost, drought and salinity. Priority was given to peer-reviewed sources with complete bibliographic records and direct relevance to pistachio. General-crop reviews were retained only for definitions or well-established mechanisms and were not counted as direct evidence of efficacy in pistachio.

For the present revision, the source manuscript was also audited for citation-to-claim consistency. Statements that were species-specific but supported only by work in another crop were removed or rewritten as mechanistic hypotheses. Citations appearing in the text without a corresponding bibliographic entry were not retained as evidence. Likewise, nanoparticle and synthetic-hormone treatments were not presented as established pistachio biostimulants because the available source material did not provide sufficiently direct, species-specific evidence for that classification or for the claimed effects.

Evidence was interpreted in three tiers. Tier 1 comprises replicated orchard or field studies with agronomic or multi-season outcomes. Tier 2 comprises controlled experiments on pistachio seedlings or rootstocks reporting physiological, nutritional or molecular endpoints. Tier 3 comprises mechanistic evidence from other plant species. This is a critical review rather than a meta-analysis because products, genotypes, stress protocols and endpoints are too heterogeneous for a defensible pooled effect size.

Table 1. Operational boundaries used in this review

Category	Working definition	Examples	Treatment in review
Microbial biostimulant	AMF or PGPR applied mainly to improve plant nutrition processes or abiotic-stress tolerance.	Rhizophagus/other AMF; characterized PGPR strains	Core evidence
Non-microbial biostimulant	Complex biological substance acting beyond direct nutrient supply.	<i>Ascophyllum nodosum</i> extract; humic/fulvic fractions	Core evidence
Organic amendment	Bulk material that modifies soil physical, chemical and biological conditions.	Compost; vermicompost	Included, but effects are not assumed to be purely biostimulant
Fertilizer	Input whose primary function is nutrient delivery.	N, P, K, Zn or B fertilizer	Comparator or co-treatment; not a biostimulant by default
Plant growth regulator	Defined hormone or synthetic analogue acting directly on development.	Auxins; gibberellins; cytokinins	Kept separate from core biostimulant evidence
Biocontrol agent	Input primarily intended to suppress a pest or pathogen.	Antagonistic microorganism	Outside core scope unless a distinct biostimulant function is tested

Source: terminology adapted from du Jardin (2015) and Regulation (EU) 2019/1009.

3. What the Direct Pistachio Evidence Supports

3.1. Arbuscular mycorrhizal fungi: the strongest pistachio-specific proof of concept

Among the major biostimulant groups, AMF have the strongest direct evidence in pistachio. Under greenhouse drought, mycorrhizal inoculation improved seedling growth and mineral acquisition and was associated with increases in osmoprotective or antioxidant-related metabolites (Abbaspour et al., 2012). A separate experiment with two pistachio cultivars reported better photochemical efficiency, pigment status and gas exchange under mild to moderate water deficit, while the benefit was much smaller under severe stress (Bagheri et al., 2011). This response pattern is scientifically important because it indicates that biostimulation may widen the tolerance window without removing the physiological limits imposed by extreme water shortage.

Salinity studies provide a similarly coherent, but still mainly controlled-environment, picture. Abbaspour et al. (2021) reported that AMF symbiosis altered physiological responses, ion distribution and relevant gene expression in salt-stressed pistachio. Fattahi et al. (2021) found improved nutrient uptake and oxidative balance across pistachio rootstocks exposed to drought and salinity, with the magnitude of response varying among rootstocks. Safipour Afshar and Abbaspour (2023) further linked mycorrhizal symbiosis under salinity to antioxidant pathways and altered gene expression. Taken together, these studies support mechanisms involving mineral acquisition, ion homeostasis and oxidative protection.

The practical inference should remain conditional. Colonization success depends on inoculum quality, host genotype, soil phosphorus, moisture, temperature and

prior management. A nursery application in a controlled substrate is therefore not equivalent to inoculation of an established orchard. Future trials should report colonization and persistence in the root system rather than only the nominal application rate of a commercial product.

3.2. Plant growth-promoting rhizobacteria: biologically credible, strain-dependent responses

PGPR are attractive for pistachio because local strains can be selected from environments characterized by salinity, drought or alkaline soils. Khalilpour et al. (2021) evaluated indigenous stress-tolerant bacterial isolates on pistachio seedlings under combined salinity and reduced irrigation. Inoculated plants showed improvements in growth, relative water content, pigment and photosynthetic traits, and K⁺/Na⁺ balance. The study also characterized plant-growth-promoting traits of the selected isolates, providing a stronger mechanistic link than a product trial in which microbial identity is unknown.

Salimi et al. (2023) reported a halotolerant *Paenarthrobacter nitroguajacolicus* strain with phosphate- and zinc-solubilizing activity and growth-promoting effects on *Pistacia vera*. More recent work with haloalkaliphilic bacteria also indicates that cultivar, strain and environmental context interact strongly (Eskandari Torbaghan et al., 2025). The main implication is that 'PGPR' is not a uniform active ingredient. Strain identity, viable count, root colonization or persistence, and compatibility with the target rootstock should be treated as essential experimental information.

3.3. Seaweed extracts and fulvic substances: promising orchard physiology, limited generalization

Non-microbial products have a smaller but increasingly relevant pistachio evidence base. Foliar *Ascomyces* extract was evaluated on mature 'Kaleh-Ghoochi' trees, where concentration and timing influenced carbohydrates, proteins, phenolics and antioxidant-enzyme activity (Nikoogoftar-Sedghi et al., 2023). These findings support a physiological response under orchard conditions, but changes in biochemical markers should not be interpreted as proof of durable yield improvement or disease control.

Fulvic acid has also produced a coherent physiological signal. Nikoogoftar-Sedghi et al. (2024) reported enhanced antioxidant capacity, pigment status and selected mineral traits following foliar application in pistachio. This evidence is useful because it moves beyond generic crop extrapolation, yet product origin and chemical characterization remain important: humic and fulvic materials can differ substantially in composition, and an application rate cannot be generalized across formulations without chemical information.

3.4. Compost, vermicompost and combined interventions

Organic amendments can improve water retention, nutrient supply and microbial habitat simultaneously, making them agronomically valuable but difficult to classify mechanistically. Paymaneh et al. (2023) found that compost and/or vermicompost combined with AMF improved growth and nutrient acquisition of drought-stressed pistachio seedlings. The result supports integrated nursery-substrate management, but factorial designs are required to distinguish improved soil physical properties and nutrient delivery from a specific AMF effect or true synergy between components.

Table 2. Direct pistachio evidence retained for the critical synthesis

Study	Intervention	Plant material / setting	Main reported outcome	Critical interpretation
Bagheri et al., 2011	AMF	Two <i>P. vera</i> cultivars; greenhouse drought	Improved PSII-related performance, pigments and gas exchange mainly under mild/moderate stress.	Tier 2; benefits weakened as stress became severe.

Abbaspour et al., 2012	AMF	P. vera seedlings; greenhouse drought	Higher growth, mineral acquisition and stress-related metabolites.	Tier 2; short controlled experiment.
Abbaspour et al., 2021	AMF	P. vera seedlings; NaCl stress	Improved biomass, nutrition, ion balance and gene-expression responses.	Tier 2; comparatively strong mechanistic depth.
Fattahi et al., 2021	AMF	Four pistachio rootstocks; drought and salinity	Improved nutritional uptake and oxidative balance; responses varied by rootstock.	Tier 2; clear genotype dependence.
Khalilpour et al., 2021	PGPR	P. vera seedlings; combined drought/salinity	Improved growth, water status, photosynthetic traits and ion balance.	Tier 2; indigenous isolates, controlled conditions.
Salimi et al., 2023	PGPR	P. vera seedlings	Halotolerant, P/Zn-solubilizing strain improved plant-growth-related traits.	Tier 2; strain-specific evidence.
Paymaneh et al., 2023	AMF + organic amendments	Pistachio seedlings; drought	Improved growth and nutrient acquisition.	Tier 2; treatment components have overlapping functions.
Nikoogoftar-Sedghi et al., 2023	A. nodosum extract	Mature pistachio orchard	Timing- and dose-dependent changes in stress-related biochemical traits.	Field relevance; no basis for claiming disease control.
Nikoogoftar-Sedghi et al., 2024	Fulvic acid	Pistachio orchard	Enhanced antioxidant capacity, pigments and nutritional quality traits.	Field relevance; formulation-specific and not equivalent to a yield claim.
Eskandari Torbaghan et al., 2025	Haloalkaliphilic PGPR	P. vera; saline-alkaline conditions	Strain- and cultivar-dependent vegetative, biochemical and nutritional responses.	Field/controlled bridge; strong interaction effects.

4. Disease Resistance: A Claim That Requires Stricter Evidence

The disease-resistance component of the original manuscript was the area most vulnerable to overstatement. Several broad mechanisms—competition in the rhizosphere, antimicrobial metabolite production and induced systemic resistance—are well documented for beneficial microorganisms in plants generally (Backer et al., 2018; Calvo et al., 2014). Those mechanisms are biologically plausible in pistachio, but plausibility is not equivalent to a demonstrated reduction in disease incidence or severity in *Pistacia vera*.

For this reason, the revised synthesis does not state that seaweed extracts, humic substances, melatonin, nanoparticles or generic microbial formulations have been proven to control *Fusarium*, *Botryosphaeria*, *Phytophthora* or other pathogens in pistachio unless a pistachio experiment measured the relevant pathosystem directly. Physiological improvement can increase overall plant resilience, but it should be described as improved stress status unless pathogen challenge, disease rating or pathogen load was actually assessed.

The regional contribution of Nazarova et al. (2023) is therefore important in a different way. By documenting *Septoria pistaciae* and its biological characteristics in Uzbekistan, the study establishes a locally relevant pathogen context for pistachio research. In future biostimulant trials, such information can inform disease scouting, sampling windows and the choice of disease endpoints. It should not be used as evidence of biostimulant efficacy because no such treatment effect was the purpose of that study.

A stronger research design for disease-related claims would include a defined host genotype, a characterized pathogen or natural disease-pressure description, a biostimulant treatment with known composition, an appropriate untreated control, repeated disease-severity assessments, plant growth and physiological measurements, and—where feasible—pathogen quantification. A microbial treatment whose primary function is antagonistic pathogen suppression should also be identified as a biocontrol agent unless an independent biostimulant function is demonstrated.

5. Mechanisms: Where the Evidence Is Strong and Where It Remains Inferential

5.1. Nutrient acquisition and root function

Improved root function and nutrient acquisition are among the most consistent responses reported for microbial biostimulants. AMF extend the effective soil volume explored by the root system and can improve acquisition of relatively immobile nutrients. In pistachio, improved mineral status under drought or salinity has been reported in AMF studies (Abbaspour et al., 2012; Fattahi et al., 2021). PGPR may contribute through phosphate or zinc solubilization, siderophore production, phytohormone-related processes and modification of root architecture (Backer et al., 2018; Salimi et al., 2023).

5.2. Water relations and photosynthetic performance

Under water deficit, better root exploration and osmotic adjustment can support leaf water status and photosynthetic function. Pistachio experiments report improved photochemical performance, pigments, relative water content and gas exchange under selected AMF or PGPR treatments (Bagheri et al., 2011; Khalilpour et al., 2021). Broader meta-analytic evidence also supports positive effects of AMF on photosynthesis, water status and gas exchange under salt stress, although the magnitude of response is context dependent (Chandrasekaran et al., 2019).

5.3. Ion homeostasis and oxidative regulation

Salinity tolerance depends partly on the ability to limit Na^+ accumulation while maintaining essential cations and controlling oxidative damage. In pistachio, AMF and bacterial treatments have been associated with improved K^+/Na^+ relationships and lower salt injury, while some studies report changes in antioxidant activity and stress-responsive gene expression (Abbaspour et al., 2021; Fattahi et al., 2021; Safipour Afshar and Abbaspour, 2023). These findings strengthen the mechanistic case, but gene expression at one or a few sampling points does not by itself establish a complete causal pathway.

5.4. Rhizosphere interactions and induced resistance

The rhizosphere is a plausible bridge between improved nutrition and plant defense. Beneficial microorganisms can alter root exudation, nutrient competition and immune signaling, and PGPR commercialization literature describes multiple pathways by which bacterial inoculants affect plant performance (Backer et al., 2018). In the present review, however, these pathways are treated as mechanistic context rather than direct proof of pathogen resistance in pistachio. This distinction is necessary to keep conclusions aligned with the actual measurements in the available *Pistacia* studies. A

conceptual synthesis of these interacting pathways and their expected functional outcomes is presented in Figure 1.

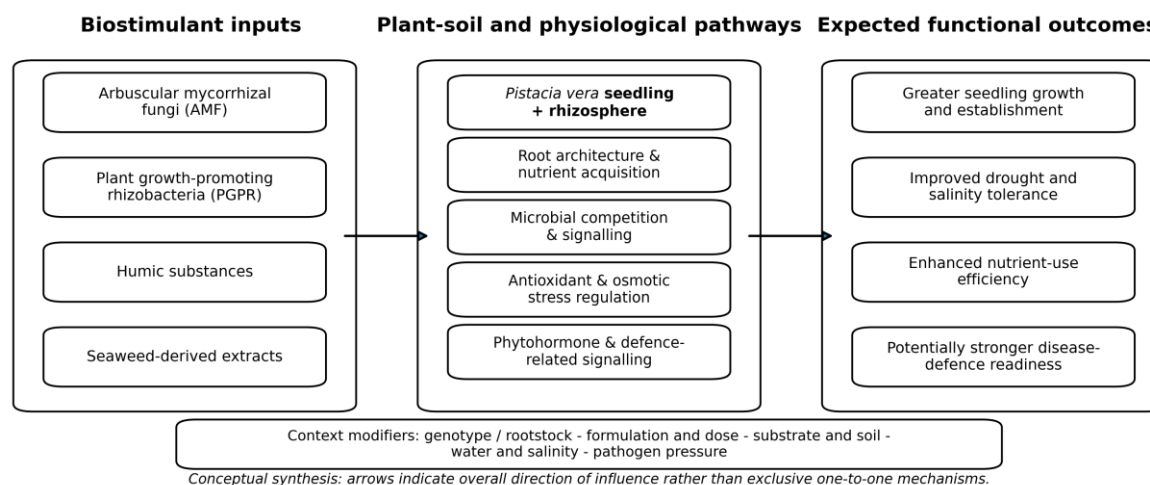


Figure 1. Proposed mechanisms of biostimulant action in *Pistacia vera* L. seedlings. Biostimulant classes are linked to plant-soil and physiological pathways and then to expected functional outcomes. Disease-defence effects are presented as conditional because direct pathogen-specific evidence in pistachio remains limited.

6. Why Promising Physiological Results Do Not Yet Equal A Universal Recommendation

Five limitations recur across the evidence base. First, most experiments use seedlings or young rootstocks, whereas commercial decisions often concern grafted, bearing trees. Second, many experiments are short relative to the perennial life cycle of pistachio and therefore cannot evaluate persistence, carry-over effects or alternate bearing. Third, microbial inocula and non-microbial formulations are not always characterized sufficiently for replication. Fourth, biochemical and physiological proxies are more common than endpoints such as survival after outplanting, marketable yield, split-nut percentage, blankness, disease incidence or economic return. Fifth, publication bias is likely: positive responses are more visible than null or negative outcomes.

The correct practical position is therefore conditional rather than promotional. AMF and locally adapted PGPR are credible candidates for nursery establishment and stress-prone root zones when microbial identity and colonization are verified. Foliar seaweed or fulvic products may improve selected physiological traits in orchards, but their value should be tested against appropriate controls and over sufficient time to capture environmental and phenological variability. None should be presented as a replacement for irrigation scheduling, salinity management, balanced fertilization, sanitation or

disease-specific control measures.

7. Research Priorities for Forestry Nurseries and Central Asian Dryland Systems

For Central Asia, the highest-value question is not which imported product produces the largest short-term increase in chlorophyll. The more relevant question is whether locally adapted microorganisms or well-characterized non-microbial products can improve establishment and performance under the combined stresses encountered in practice: saline irrigation water, episodic drought, heat, nutrient imbalance and locally important diseases.

Multi-location studies should compare locally isolated AMF or PGPR with at least one well-characterized benchmark product across key rootstocks or seed sources. Nursery trials should extend into the outplanting phase so that early physiological gains can be linked to survival and growth after establishment. Orchard trials should include at least two complete seasons where feasible and should report treatment composition, dose, timing, irrigation and nutrient background, soil electrical conductivity, rootstock and scion identity, and weather conditions.

Disease monitoring should be integrated rather than added after the fact. In regions where *Septoria pistaciae* or other pistachio pathogens are present, disease incidence and severity should be recorded alongside

growth and physiological measurements. The regional work of Nazarova et al. (2023) provides a basis for defining locally relevant disease observations in Uzbekistan. Future studies could then test whether a biostimulant changes host vigor only, reduces disease, or produces both effects.

Remote and proximal sensing may strengthen such trials by adding canopy temperature, vegetation indices or spatial response maps, but these measurements should

complement rather than replace field disease scores, root-zone measurements, biomass, survival, yield and quality endpoints. The strongest international contribution would be a design that links mechanism to management value and reports effect sizes with confidence intervals rather than relying only on statistical significance. The hierarchy of evidence and the priority research gaps identified in this review are summarized in Figure 2.

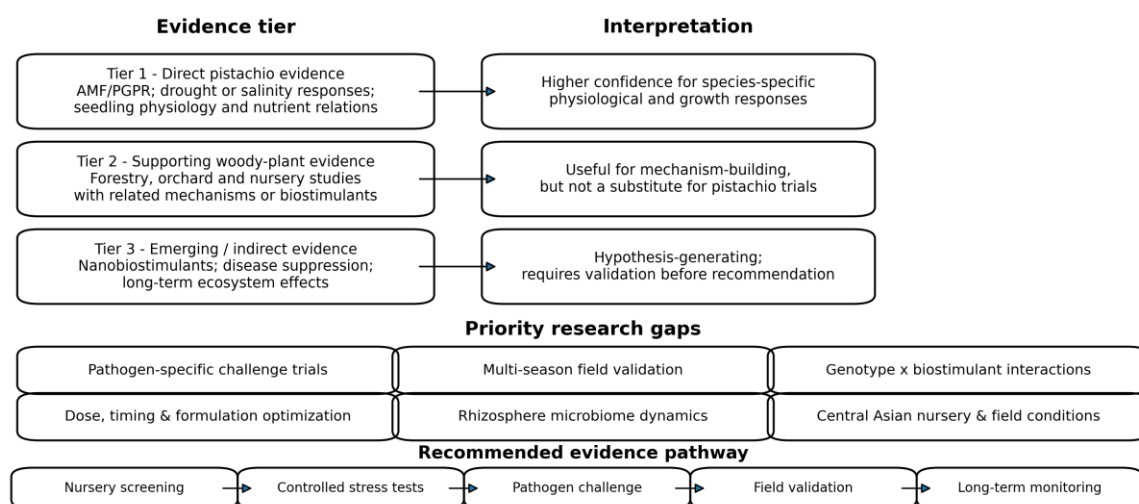


Figure 2. Evidence framework and research gaps for biostimulant use in *Pistacia vera* L. Direct pistachio evidence is distinguished from supporting woody-plant evidence and emerging or indirect evidence; the recommended pathway progresses from nursery screening to long-term validation.

Table 3. Minimum design features for the next generation of pistachio biostimulant studies

Design domain	Minimum reporting requirement	Why it matters
Biological identity	AMF colonization; bacterial strain identity and viable count; chemical characterization for extracts.	Confirms that the active treatment was present and makes replication possible.
Plant material	Named cultivar/scion and rootstock, age, propagation method and baseline vigor.	Separates treatment effects from genotype and developmental stage.
Environment	Soil texture, pH, EC, organic carbon, available nutrients, irrigation-water EC and weather.	Defines the environmental domain in which the treatment may work.
Comparators	Untreated control, nutrient-matched control where relevant, and current best management.	Distinguishes biostimulation from nutrient supply and background management.
Time scale	Nursery-to-field follow-up; multi-season orchard studies where feasible.	Tests persistence and avoids conclusions based on transient proxy responses.

Design domain	Minimum reporting requirement	Why it matters
Core endpoints	Colonization/persistence, water status, gas exchange, ion balance, survival/growth, disease incidence/severity, yield and quality as appropriate.	Links mechanism to practical performance.
Statistics	Pre-specified primary outcome, adequate replication, blocking/site effects, effect sizes and confidence intervals.	Improves reproducibility and reduces selective interpretation.
Economics and safety	Product and application cost, potential water/fertilizer savings, return on investment and relevant safety checks.	Supports realistic adoption and regulatory evaluation.

8. Conclusions

The available evidence supports plant biostimulants as promising, context-dependent tools for pistachio production, but the maturity of evidence differs sharply among product classes and claimed outcomes. AMF have the strongest direct support for improving nutrient acquisition, water relations, ion balance and oxidative stability in stressed pistachio seedlings and rootstocks. PGPR results are encouraging, particularly for locally adapted strains under salinity and drought. Seaweed extract and fulvic acid have produced useful orchard-level physiological responses, but the evidence base is still too limited for broad claims about durable yield benefits or pathogen control.

Disease resistance requires a higher evidential threshold than improved vigor. The presence and biological significance of pistachio pathogens in Uzbekistan, including *Septoria pistaciae* documented by Nazarova et al. (2023), strengthen the rationale for integrating disease measurements into future trials. They do not justify assuming that a biostimulant will control disease. The next phase of research should therefore combine careful product characterization, rootstock-aware experimental design, realistic multi-stress conditions, disease assessment and multi-season agronomic outcomes. Such work would provide a more credible basis for using biostimulants in nursery, orchard and dryland forestry-related systems.

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