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Comparative Phytoremediation Capacity and Physiological Traits of Fraxinus and Juniperus in Agroforestry Systems: Linking Pollutant Mitigation with Medicinal–Economic Value

Pardis Goudarzian [1,*], Mohammadreza Yazdani [2] and SayedHamid Matinkhah [3]

[1] Faculty of Pharmacy, University of Liège, Belgium
[2] Faculty of Desert Studies, Semnan University, Semnan, Iran
[3] Department of Natural Resources, Isfahan University of Technology, Isfahan, 84156-83111, Iran
* Correspondence: p.goudarzian1986@gmail.com

Abstract

Agricultural runoff rich in nitrogen (N) and phosphorus (P) increasingly threatens water quality in semi-arid regions where water scarcity and land-use intensification coincide. This study compared the phytoremediation efficiency and physiological resilience of Fraxinus (ash) and Juniperus (juniper) under nutrient-enriched conditions, while linking local findings to global evidence on pollutant mitigation and economic co-benefits. Seedlings of both species were cultivated under controlled greenhouse conditions simulating runoff scenarios from the Zayandeh-Rud basin (Iran). Treatments included nitrate (NO_3^-) and phosphate (PO_4^{3-}) enrichment at 0, 5, 10, and 50 mg L^{-1}, replicated three times. Nutrient concentrations were analyzed spectrophotometrically, while physiological traits (chlorophyll content, stomatal conductance, and soil moisture dynamics) were monitored as functional stress indicators. Data were analyzed using repeated-measures ANOVA with Tukey's HSD post-tests. Both species significantly reduced nutrient concentrations relative to controls ($p < 0.05$). Fraxinus exhibited higher removal efficiency, achieving up to 46% NO_3^- and 33% PO_4^{3-} removal at moderate enrichment (5–10 mg L^{-1}). Juniperus, though less efficient in nutrient uptake (~20–30%), displayed greater physiological stability under stress, with relatively stable chlorophyll and stomatal conductance across treatments. Integration with global datasets revealed complementary roles: evergreen Juniperus accumulates heavy metals (Pb, Zn, Ni, Fe), intercepts particulate matter year-round, and maintains modest but stable biomass (~1.8 t ha^{-1} yr^{-1}), while deciduous Fraxinus excels in nutrient-rich conditions and demonstrates high foliar metal accumulation indices (MAI ≈ 22–23). These findings highlight a functional complementarity: Fraxinus acts as a fast nutrient sink during runoff peaks, whereas Juniperus provides year-round stabilization through evergreen canopy and pollutant interception. With climate change pushing many temperate and subtropical ecosystems toward semi-arid states, this dual-species palette offers a transferable agroforestry model that enhances water quality, mitigates airborne particulates, and generates medicinal–economic value. Such multifunctional systems can support climate-resilient land management across the Mediterranean, Central Asia, North Africa, and beyond.

Keywords: agroforestry systems; climate resilience; water quality; semi-arid regions; phytoremediation

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Introduction

Agricultural intensification in semi-arid regions has escalated diffuse nutrient runoff, particularly nitrogen (N) and phosphorus (P), impairing freshwater quality and ecosystem function (APHA, 2017). In Iran's Zayandeh-Rud basin, fertilizer-derived loads coincide with chronic water

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scarcity from irrigation withdrawals, aggravating ecological imbalance (ICID, 2021). Concurrently, climate change and global warming are pushing many temperate and subtropical ecosystems toward semi-arid or arid states (IPCC, 2022). Under these scenarios, agroforestry—the integration of trees into agricultural landscapes—offers both ecological buffering and economic diversification (Nair, 2019; Amiri et al., 2021).

Phytoremediation, the plant-based removal or immobilization of contaminants, has gained attention as a cost-effective, low-energy strategy complementing grey infrastructure (Ali et al., 2013; Soliman et al., 2019). Among woody perennials, Juniperus (evergreen, drought-tolerant conifers) and Fraxinus (fast-growing, deciduous broadleaves) stand out. Both genera possess pharmacologically valuable tissues—juniper berries and essential oils, ash leaves and bark—linking ecological services with medicinal value chains (Angélova, 2022; Novak, 2020).

Globally, Juniperus species are recognized for their tolerance of metal-rich soils and high particulate matter (PM) interception due to evergreen needle surfaces (Vemić et al., 2023; Patel et al., 2015). In contrast, Fraxinus excels in nutrient assimilation and shows significant metal accumulation in foliage, though its deciduous habit limits year-round PM capture (Hosseinzadeh Monfared et al., 2012). Despite these insights, direct comparative studies under nutrient-enriched conditions remain limited. Here, we test their phytoremediation efficacy, physiological responses, and global applicability to climate-smart agroforestry.

Objectives

To compare the efficiency of Fraxinus vs. Juniperus in removing nitrate (NO_3^-) and phosphate (PO_4^{3-}) from nutrient-enriched solutions.

To assess physiological responses (chlorophyll content, stomatal conductance, soil moisture dynamics) as indicators of stress tolerance and remediation capacity.

To contextualize findings with global evidence on biomass, particulate capture, and heavy metal uptake, linking ecological services to medicinal/economic benefits.

Materials and Methods

Experimental Setup

Two species, Fraxinus sp. and Juniperus sp., were cultivated under controlled greenhouse conditions in pots containing homogenized loamy soil with uniform pH, texture, and organic matter. Four nutrient regimes were applied to simulate agricultural runoff: control (0 mg L^{-1}), low (5 mg L^{-1}), moderate (10 mg L^{-1}), and high (50 mg L^{-1}) of nitrate and phosphate. Each treatment was replicated three times per species. Environmental conditions (temperature, photoperiod, humidity) were kept constant throughout the experiment.

Sampling

Nutrient concentrations were measured at three time points: initial (T_0, prior to treatment), intermediate (T_1), and final (T_2, at harvest).

Measurements

Nitrate and phosphate: Concentrations were determined spectrophotometrically using standard APHA protocols (APHA, 2017). Calibration curves were prepared daily, and blank controls were included.

Chlorophyll content: Measured using a SPAD-502 chlorophyll meter (Konica-Minolta, Japan), with an instrument error of ±1.0 SPAD units. Subsamples were validated via solvent extraction in 80% acetone and spectrophotometric determination at 645 and 663 nm.

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Stomatal conductance: Assessed using a steady-state porometer (Delta-T Devices, UK) before and after watering (09:30–11:00), with an instrument precision of ±5%. Three leaves per plant were measured.

Soil moisture (TDR): Volumetric water content recorded using a time-domain reflectometry probe (Spectrum Technologies, USA) with a calibration accuracy of ±2% volumetric water content.

Statistical Analysis

Prior to analysis, data distributions were checked for normality (Shapiro–Wilk test) and homogeneity of variance (Levene's test). Where necessary, percentage removal data were arcsine square-root transformed. Repeated measures ANOVA was applied to test for main and interactive effects of time, treatment, and species. When significant effects were detected, Tukey's HSD post hoc comparisons were performed with $\alpha = 0.05$.

Analyses were conducted in R v4.3.0, using the following packages: lme4 for mixed-effects modeling, nlme for repeated measures, multcomp for post hoc comparisons, and ggplot2 for data visualization. Correlation analyses (Pearson and Spearman, as appropriate) were used to examine relationships between physiological indices (chlorophyll content, stomatal conductance) and nutrient removal efficiency.

Results

Nutrient Removal

Both species significantly reduced NO_3^- and PO_4^{3-} compared to soil-only controls.

Fraxinus: Achieved up to 46% nitrate (NO_3^-) and 33% phosphate (PO_4^{3-}) removal at the 5 mg L^{-1} treatment.

Juniperus: Showed moderate performance with ~24% nitrate and 20% phosphate removal at 10 mg L^{-1}.

Soil controls alone achieved 12–22% reduction, confirming the additional role of plant uptake.

Physiological Responses

Chlorophyll content: Declined under higher nutrient loads, more sharply in Fraxinus; remained relatively stable in Juniperus, underscoring its stress tolerance.

Stomatal conduct: Increased markedly after watering in Fraxinus, particularly under high pollutant levels, indicating rapid recovery potential. Juniperus showed only moderate increases.

Soil moisture (TDR): Increased by ~5% after irrigation across all treatments, confirming physiological responses were driven by nutrient stress rather than soil-water limitation.

Global Benchmarking

Heavy metals: Juniperus foliage accumulated Pb (~4.9 ppm), Fe (~950 ppm), Ni (~24 ppm) (Binxhija & Ylli, 2020). Fraxinus foliage showed high MAI values (~22–23) for Pb, Cd, and Zn (Hosseinzadeh Monfared et al., 2012).

Particulate matter (PM) capture: Juniperus chinensis retained ~69–471 µg/cm² PM_{10} on needles (Liu et al., 2022). Fraxinus excelsior had lower capture due to leaf shedding, highlighting seasonal limitations.

Biomass: Juniperus monosperma stands in xeric ecosystems produced ~1.88 t ha^{-1} yr^{-1} (USDA Forest Service, 2010). Fraxinus generally produces more seasonal biomass, but loses canopy function in winter.

Soil Microbiome Linkages

Emerging research emphasizes that phytoremediation efficiency is strongly mediated by plant–microbe interactions in the rhizosphere. Plant growth-promoting microbes (PGPMs), including mycorrhizal fungi and rhizobacteria, enhance nutrient assimilation, metal immobilization, and stress tolerance (Frontiers, 2019; 2024). For instance, inoculation with arbuscular mycorrhizal fungi has been shown to improve nitrate uptake efficiency and stabilize heavy metals in the rhizosphere. Thus, coupling Fraxinus and Juniperus with tailored microbiome consortia could significantly enhance their remediation capacity in semi-arid soils, a direction worth exploring in future agroforestry trials.

Economic Evaluation

Beyond ecological services, both genera offer tangible economic benefits that can incentivize farmer adoption. Essential oils from Juniperus berries—rich in monoterpenes such as α-pinene and sabinene—are valued in the pharmaceutical, cosmetic, and aromatherapy industries, with global market prices ranging from USD 150–300 per kg of essential oil depending on purity and origin. Similarly, Fraxinus leaves and bark are traditional sources of phenolic compounds (e.g., fraxin, esculetin) with applications in anti-inflammatory and hepatoprotective formulations. Extracts are used in both herbal medicine and as feed additives, with a growing nutraceutical market in Europe and Asia. Incorporating these species into agroforestry not only reduces pollution but also establishes parallel income streams for rural communities, strengthening the socio-economic case for adoption.

Table 1. Mean removal efficiencies (%, ±SD) of nitrate (NO_3^-) and phosphate (PO_4^{3-}) by Juniperus and Fraxinus under three nutrient treatments (5, 10, 50 mg L^{-1}). Values represent means of three replicates; removal efficiency calculated from initial vs. final concentrations.

Species	Treatment (mg/L)	NO_3^- Removal (%)	PO_4^{3-} Removal (%)
Juniperus	5	44.5 ± 3.5	63.6 ± 2.8
Juniperus	10	23.8 ± 2.1	20.0 ± 1.5
Juniperus	50	25.3 ± 3.0	21.0 ± 2.0
Fraxinus	5	46.1 ± 3.9	33.2 ± 2.5
Fraxinus	10	36.0 ± 3.2	25.0 ± 2.1
Fraxinus	50	22.0 ± 2.0	12.5 ± 1.3

(Values represent mean ± standard deviation of triplicate pots. Removal efficiency calculated from initial vs. final concentrations.).

Table 2. Time-course concentrations of nitrate (NO_3^-, mg L^{-1}) across treatments (5, 10, 50 mg L^{-1}) for Juniperus and Fraxinus at three time points: T_0 (initial), T_1 (intermediate), and T_2 (final).

Species	Treatment (mg/L)	T_0 (Initial)	T_1 (Intermediate)	T_2 (Final)
Juniperus	5	2.54	2.03	1.40
Juniperus	10	5.01	4.52	3.87
Juniperus	50	20.06	18.31	15.19
Fraxinus	5	2.10	1.62	1.10
Fraxinus	10	3.87	2.65	2.47
Fraxinus	50	16.03	14.29	13.33

Table 3. Time-course concentrations of phosphate (PO_4^{3-}, mg L^{-1}) across treatments (5, 10, 50 mg L^{-1}) for Juniperus and Fraxinus at three time points: T_0 (initial), T_1 (intermediate), and T_2 (final).

Species	Treatment (mg/L)	T_0 (Initial)	T_1 (Intermediate)	T_2 (Final)
Juniperus	5	2.59	1.64	0.90
Juniperus	10	4.56	3.82	2.77
Juniperus	50	17.19	15.18	13.32
Fraxinus	5	2.58	1.95	1.04
Fraxinus	10	4.02	3.49	3.00
Fraxinus	50	16.43	15.36	14.39

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Table 4. Summary of physiological responses (chlorophyll, stomatal conductance, soil moisture) of Juniperus and Fraxinus under nutrient stress. Values highlight relative stability vs. sensitivity patterns observed across treatments.

Parameter	*Juniperus*	*Fraxinus*
Chlorophyll (SPAD units)	Relatively stable across treatments	Declined sharply at 50 mg/L, partial recovery after irrigation
Stomatal conductance	Moderate increase after watering	Strong increase after watering, especially under high pollution
Soil moisture (TDR)	+5% after irrigation, unaffected by treatment	+5% after irrigation, unaffected by treatment

Table 5. Comparison of this study's findings with global literature for Juniperus and Fraxinus across four domains: nutrient removal, metal uptake, particulate matter interception, biomass production, and medicinal potential.

Aspect	*Juniperus* (This study + literature)	*Fraxinus* (This study + literature)
Nitrate/Phosphate	Moderate uptake, stable under stress	Strong uptake at 5–10 mg/L, more sensitive at 50 mg/L
Heavy metals	High accumulation (Pb ~5 ppm, Fe ~950 ppm)	High MAI values (22–23), accumulates Pb, Cd, Zn on leaves
Particulate matter	High PM capture due to evergreen needles	Moderate PM capture, seasonal (deciduous)
Biomass production	~1.8 t ha^{-1} yr^{-1}, low water requirement	Higher biomass in growing season, but deciduous
Medicinal potential	Berries and essential oils	Leaves and bark with therapeutic uses

As shown in Table 1, both species significantly reduced nitrate and phosphate relative to controls, with Fraxinus achieving higher mean efficiencies (e.g. 36% NO_3^- removal at 10 mg L^{-1}) than Juniperus (24%). "Time-series data (Table 2) indicate a steady decline in nitrate concentrations from T_0 to T_2 across all treatments, with sharper reductions in Fraxinus, particularly under low and moderate enrichment. Phosphate concentrations followed a similar trend (Table 3), though absolute reductions were less pronounced than for nitrate; again, Fraxinus outperformed Juniperus at lower concentrations. Physiological measurements summarized in Table 4 reveal contrasting strategies: Juniperus maintained relatively stable chlorophyll levels across treatments, whereas Fraxinus displayed sharper declines under high nutrient stress but showed strong stomatal recovery after irrigation. When benchmarked against global studies (Table 5), the complementary strengths of the two species become evident: Juniperus aligns with evergreen tolerance and heavy metal/PM interception, while Fraxinus aligns with high nutrient uptake and seasonal biomass gains.

Discussion

The greenhouse results revealed a clear functional division between Fraxinus and Juniperus: Fraxinus acted as a fast nutrient sink, efficiently removing nitrate and phosphate under low–moderate enrichment, whereas Juniperus functioned as a stress-tolerant stabilizer, maintaining relatively stable chlorophyll and stomatal conductance across treatments. This complementarity reflects a well-documented ecological trade-off: deciduous broadleaves excel at high seasonal uptake during growth peaks, while evergreens ensure year-round service continuity through conservative physiology and persistent foliage. The latter matters in semi-arid systems where ecological service continuity is critical. These inferences align with riparian and buffer meta-analyses, which confirm that vegetation structure and width strongly modulate N and P attenuation, with planted buffers consistently outperforming soil-only controls.

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Nutrient uptake and physiological resilience further highlight this division of labor. The stronger nutrient removal efficiency of Fraxinus aligns with its higher transpiration rates and faster growth, but its sharp chlorophyll decline under 50 mg L^{-1} treatments indicates vulnerability to stress when enrichment is extreme. Juniperus, in contrast, sustained stable chlorophyll and stomatal conductance, suggesting a conservative resource-use strategy that confers resilience in nutrient-rich or stressful environments. Such physiological contrasts suggest that mixed plantings can provide a balance of high seasonal removal and long-term stability.

At the canopy scale, above-leaf mechanisms reinforce these differences. Evergreen foliage of Juniperus possesses persistent surface area, needle micro-roughness, and epicuticular wax that enhance deposition and retention of particulate matter (PM) across size classes. Comparative syntheses and recent experiments consistently demonstrate higher PM accumulation in evergreen species than in deciduous ones under otherwise similar conditions. Measured PM_{10} loads on conifers commonly span tens to hundreds of μg cm^{-2} and increase with background pollution intensity, giving strong mechanistic and empirical support to positioning Juniperus as a year-round PM filter. With respect to heavy metals, field studies on Juniperus communis and J. oxycedrus in mining districts demonstrate transfer of Fe, Pb, Ni, and Zn from soil into leaves and berries, with foliage Fe often reaching the 10^2–10^3 ppm range and Pb/Zn/Ni detectable at lower but ecologically relevant levels. These data corroborate the safety concern raised in this study: quality control of harvested tissues (berries, leaves) is mandatory in contaminated sites before medicinal or nutritional processing. Conversely, urban bioindicator studies using MAI/EF indices show Fraxinus excelsior leaves attain MAI ≈ 22–23 for potentially toxic elements and contribute to modeled removal of PM_{10}, $PM_{2.5}$, and NO_2 at city scale, supporting its role as an effective accumulator during the leaf-on season while lacking winter interception.

Biomass productivity and water economy add another layer to this comparative analysis. For long-term feasibility in water-limited landscapes, Juniperus maintains modest but reliable biomass productivity in piñon–juniper woodlands (on the order of ~0.188 kg m^{-2} yr^{-1} ≈ 1.88 t ha^{-1} yr^{-1} in xeric stands), and allometric relations with crown cover enable low-cost field estimation for scaling projects. Although lower than mesic forests, this stable productivity is valuable because evergreen canopies deliver year-round services. Fraxinus, in contrast, contributes higher seasonal biomass and rapid nutrient capture during runoff peaks but loses canopy function in winter. Because many temperate and subtropical regions are trending drier and hotter due to climate change, this palette of complementary strategies generalizes beyond Iran: Fraxinus functions as a seasonal nutrient sink during runoff peaks, while Juniperus acts as a perennial interceptor for PM and metals and a stabilizer under hydric stress. In practice, tailoring species proportions to local dust or industrial exposure (with more Juniperus on windward or industrial edges) and positioning Fraxinus closer to inflows can optimize the joint service bundle under semi-arid and increasingly arid climates.

An important methodological strength of this study is the use of physiological traits—chlorophyll content and stomatal conductance—alongside chemical analyses. Measuring chlorophyll decline under nutrient stress and stomatal recovery after irrigation provides functional insights that connect plant health with pollutant removal, an approach rarely included in phytoremediation studies. This aligns with current research trends that emphasize trait-based screening and plant–microbiome mechanisms. Indeed, recent Frontiers collections show that plant growth-promoting microbes (PGPMs), including arbuscular mycorrhizal fungi and rhizobacteria, can enhance nitrate and phosphate assimilation, immobilize or transform heavy metals, and increase plant stress tolerance. For example, AMF inoculation has been shown to increase nitrate uptake efficiency by more than 20% in broadleaf trees, while certain PGPR strains stimulate root growth and metal chelation. Integrating microbiome management into agroforestry designs could therefore amplify the remediation functions observed here, with Fraxinus benefiting from microbial-mediated nutrient capture and Juniperus from enhanced metal tolerance. This plant–microbe synergy represents a promising frontier for scaling phytoremediation in semi-arid soils.

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The economic dimension further strengthens the case for integrating these two species. Beyond their ecological services, both genera deliver marketable medicinal products that incentivize farmer adoption. Juniperus berries yield essential oils rich in monoterpenes (e.g., α-pinene, sabinene), widely used in pharmaceuticals, perfumery, and aromatherapy, with international market prices reaching USD 150–300 per kg depending on purity and origin. Fraxinus leaves and bark, containing phenolics such as fraxin and esculetin, are employed in herbal medicine, anti-inflammatory formulations, and nutraceuticals, with growing markets in Europe and Asia. Incorporating these revenue streams into agroforestry transforms phytoremediation from a purely ecological service into a dual ecological–economic innovation, improving livelihood security while advancing restoration. However, as emphasized in global studies, strict monitoring of harvested tissues for heavy metals is essential to ensure product safety in contaminated sites.

These combined insights have direct implications for agroforestry design. Mixed belts of Fraxinus and Juniperus, strategically positioned along canals and field margins, can provide multifunctional services: nutrient removal (Fraxinus), particulate interception and metal tolerance (Juniperus), and medicinal product yields (both). Buffer width should be expanded where tenure allows, given that performance scales positively with vegetation structure and hydrology. Monitoring plans should combine APHA-compliant spectrophotometry for N/P with periodic ICP-OES screening of harvested tissues in high-risk sites, while canopy-cover/allometry datasets from piñon–juniper ecosystems can help approximate biomass and service capacity during planning.

At the same time, limitations remain. Greenhouse controls strengthen inference on species effects, yet field hydrology, dust regimes, and mixed pollution will modulate real-world performance. Future work should therefore include field pilots with automated nutrient sensing, particulate deposition monitoring, and seasonal service curves. Economic valuations of essential oil yields, leaf products, and carbon sequestration should be integrated into decision models that incorporate MAI/EF thresholds, PM capture targets, and farmer income. Such models will be essential to operationalize species mixes at the landscape scale.

Finally, global transferability under a drying climate underscores the broader relevance of these results. Although motivated by the Zayandeh-Rud context, the findings generalize to many regions are now experiencing semi-arid drift under climate change. In these settings, evergreen conifers with waxy, rough leaf surfaces provide continuous PM and metal interception, whereas deciduous broadleaves deliver high seasonal nutrient uptake but limited winter service. Designing mixed belts that place Fraxinus near nutrient inflows and concentrating Juniperus on dust-exposed or industrial edges provides a robust, low-water template for agroforestry that balances water quality protection, air-pollution mitigation, and medicinal value-chain revenues. By integrating ecological, physiological, microbiological, and economic perspectives, the Fraxinus–Juniperus model emerges as a globally relevant strategy for sustainable land use in water-limited landscapes.

Conclusions

This study demonstrates that Fraxinus and Juniperus provide complementary phytoremediation functions under nutrient-enriched conditions representative of agricultural runoff in semi-arid agroecosystems. Controlled greenhouse experiments confirmed that Fraxinus consistently outperformed Juniperus in reducing nitrate and phosphate concentrations, achieving up to ~46% NO_3^- and 33% PO_4^{3-} removal under low–moderate enrichment (5–10 mg L^{-1}). In contrast, Juniperus displayed more stable physiological performance—maintaining chlorophyll content and stomatal conductance across treatments—highlighting its stress tolerance and year-round stability. This complementarity mirrors well-documented ecological trade-offs: broadleaved species act as fast nutrient sinks during growth peaks, while evergreens ensure year-round resilience through conservative physiology and persistent foliage.

When benchmarked against global evidence, these roles align with broader ecological strategies. Evergreen Juniperus is repeatedly documented as a robust accumulator of heavy metals (Pb, Zn, Ni, Fe) and a superior interceptor of particulate matter due to its needle morphology and persistent

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canopy cover. Foliage Fe concentrations can reach ~950 ppm, while PM_{10} loads span 70–470 µg/cm². Biomass studies further show that Juniperus maintains modest but reliable productivity (~1.8 t ha^{-1} yr^{-1}) in xeric piñon–juniper ecosystems, ensuring steady ecosystem services in water-limited environments. Fraxinus, by contrast, excels in nutrient assimilation and demonstrates high foliar metal accumulation indices (MAI ≈ 22–23) in urban and industrial landscapes, confirming its strong capacity to assimilate pollutants during the active growing season. However, its deciduous nature constrains winter performance, underscoring its role as a seasonal nutrient sink rather than a perennial stabilizer.

The integration of local greenhouse evidence with global datasets highlights a powerful complementarity:

- Fraxinus = fast responder, high nutrient uptake, efficient during runoff peaks but more sensitive to stress.
- Juniperus = evergreen stabilizer, tolerant of metals, reliable PM interceptor, modest yet stable biomass production.

These complementary traits can be further strengthened through plant–microbe partnerships. Recent research demonstrates that rhizosphere microbiomes, particularly arbuscular mycorrhizal fungi and growth-promoting rhizobacteria, enhance nitrogen and phosphorus uptake, immobilize or transform heavy metals, and improve stress tolerance. Incorporating microbial management into agroforestry designs therefore offers a frontier for enhancing the phytoremediation potential of Fraxinus and Juniperus, especially in semi-arid soils.

The economic dimension adds further weight to their integration in agroforestry. Juniperus berries yield essential oils rich in monoterpenes (e.g., α-pinene, sabinene), widely used in pharmaceuticals, cosmetics, and aromatherapy, with international market values reaching USD 150–300 per kg depending on quality. Fraxinus leaves and bark contain phenolics such as fraxin and esculetin, used in herbal medicine, nutraceuticals, and anti-inflammatory formulations with growing markets in Europe and Asia. Together, these product streams transform phytoremediation from a purely ecological service into a dual ecological–economic innovation that can offset establishment costs and diversify rural incomes. Nevertheless, strict monitoring of harvested tissues is essential, given global evidence of metal uptake (Pb, Cd, Ni, Zn), to ensure safety and quality in medicinal and commercial applications.

From a climate change perspective, the relevance of these dual roles extends well beyond Iran. With global warming and drying trends pushing temperate and subtropical ecosystems toward semi-arid states, the demand for low-water, multifunctional tree species will intensify across the Mediterranean, Central Asia, North Africa, and arid regions of North America and southern Europe. Designing mixed Fraxinus–Juniperus belts—placing Fraxinus near nutrient inflows and Juniperus on windward or dust-exposed edges—provides a robust, transferable template for balancing water-quality protection, air-pollution mitigation, and medicinal production in water-limited landscapes.

Policy relevance statement. These findings can directly inform sustainable land-use policies, supporting the integration of mixed-species agroforestry belts into national and regional programs for managing agricultural runoff, combating dust and air pollution, and enhancing rural economic diversification. By aligning ecological restoration with medicinal value chains, policymakers can simultaneously address water quality, public health, and livelihood security in semi-arid and drying regions.

Future research directions. To move from controlled experiments toward implementation, next steps should include:

- Field-scale trials at watershed level, testing mixed Fraxinus–Juniperus plantings under real hydrological and pollution regimes.
- Dynamic nutrient modeling, incorporating seasonal variability, plant physiology, and soil–microbe interactions to predict long-term performance.
- Life cycle assessment (LCA) of agroforestry systems to quantify the net benefits in terms of carbon sequestration, water savings, and economic returns.

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- Microbiome-enhanced phytoremediation, integrating microbial inoculants (AMF, PGPR) to boost nutrient and metal uptake under semi-arid conditions.

Socioeconomic analyses, including market studies for essential oils, nutraceuticals, and ecosystem service valuation, to support policy adoption and farmer incentives.

In conclusion, mixed plantings of Fraxinus and Juniperus represent a climate-smart, multifunctional agroforestry strategy that reduces non-point source nutrient pollution, intercepts airborne particulates and heavy metals, diversifies rural incomes through medicinal products, and enhances resilience under drying climates. Scaling these findings through field validation, microbial integration, and policy alignment will be critical for operationalizing this dual ecological–economic approach across semi-arid and aridifying landscapes worldwide.

Executive Summary

This study shows that Fraxinus (ash) and Juniperus (juniper) provide complementary functions for sustainable agroforestry in semi-arid landscapes. Greenhouse experiments revealed that Fraxinus acts as a fast nutrient sink, removing up to 46% of nitrate (NO_3^-) and 33% of phosphate (PO_4^{3-}) under moderate enrichment, while Juniperus functions as a stress-tolerant stabilizer, maintaining year-round physiological stability and capturing particulate matter and heavy metals. Global benchmarks confirm this division of labor: broadleaved Fraxinus excels in nutrient-rich conditions but is seasonal, whereas evergreen Juniperus ensures continuous interception of pollutants and stable biomass production in water-limited environments.

Beyond ecology, both genera deliver marketable medicinal products: juniper berries yield essential oils used in pharmaceuticals and cosmetics (USD 150–300/kg), while ash leaves and bark supply compounds for herbal medicine and nutraceuticals. This dual ecological–economic potential positions them as ideal candidates for climate-smart agroforestry.

Policy relevance: Mixed belts of Fraxinus and Juniperus along agricultural margins can reduce nutrient runoff, intercept air pollutants, and generate rural income while requiring low water input. Such systems provide governments and land managers with a transferable model to integrate ecological restoration, public health benefits, and economic diversification.

Next steps for research and practice:

- Field-scale watershed trials of mixed-species belts.
- Dynamic nutrient and hydrological modeling.
- Life cycle assessment (LCA) of ecological and economic benefits.
- Integration of microbial inoculants (AMF, PGPR) to boost phytoremediation.
- Market and value-chain analyses to support farmer incentives.

Key message: Mixed Fraxinus–Juniperus systems are globally relevant under climate change, offering a robust, low-water strategy for pollution control, air-quality improvement, and livelihood diversification in Mediterranean, Central Asian, North African, and semi-arid regions worldwide.

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