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Review of olive pomace as an agronomic amendment in relation to current good-practice guidelines: A soil-crop-risk perspective

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ABSTRACT

This review evaluates olive-pomace-derived amendments (compost, co-compost, and biochar) as agronomic inputs, with the specific aim of defining quality gates, usage envelopes, and soil-crop-risk safeguards applicable to Mediterranean and comparable pedoclimates. We conducted a narrative review with structured screening across major databases, including only studies that applied olive-pomace products to soil and reported quantitative soil and/or crop outcomes alongside product or soil quality indicators (e.g., germination index, electrical conductivity, pH, phenolics, and total/plant-available trace metals). To translate evidence into practice, we adapted established biosolids-compliance logic into product specifications and field-monitoring protocols tailored to olive-pomace amendments. Across field and pot trials, validated compost/co-compost programs at ~5–20 t DM ha^{-1} yr^{-1} generally increased soil organic carbon (SOC), water-stable aggregation (WSA), and enzymatic activity, while maintaining or improving yields. Biochar additions (≤10 t ha^{-1}) chiefly enhanced hydraulic and structural properties and helped moderate salinity/drought stress under controlled irrigation. Effective products consistently met GI ≥80–100%, pH 6.5–8.5, context-fit EC, declining phenolics, and low plant-available trace metals. Building on these findings, we provide a tabulated toolkit—product specifications, texture/cropping-system rate bands, and a verification plan (pH, EC, TOC, WSA, enzymes, phenolics, tissue tests, and edible-crop safeguards) – that operationalizes safe, performance-oriented use. Heterogeneity in extraction technology, storage, bulking agents, and pyrolysis settings limits cross-study meta-quantification; strong context-dependence (soil type, irrigation regime, salinity) remains a key constraint on generalization. The toolkit offers ready-to-apply labels/specs, dosing ranges, and monitoring checklists for farmers, advisors, and regulators, directly supporting circular-economy valorization of olive by-products. The review bridges the policy-to-practice gap by adapting quality-gate compliance to olive-pomace products, integrating product specifications with field-level monitoring, and codifying rate/timing guidance by texture and cropping system – together forming a coherent soil–crop–risk framework to accelerate safe, scalable adoption.

Keywords: organic amendment, composting, olive pomace, biochar, soil fertility, circular economy.

INTRODUCTION

The two-phase milling process is the primary source of the enormous quantities of olive pomace (alperujo) produced by olive groves in the Mediterranean [Tortosa et al., 2023]. This residue, which is rich in organic matter, residual lipids, and phenolic compounds, may be both a soil fertility resource and a nuisance or cause phytotoxicity if not handled properly [Alburquerque et al., 2006; Fernández-Hernández et al., 2014]. Turning these stocks into safe, high-performance amendments has emerged as a top techno-environmental and agronomic concern in the context of climate mitigation and the circular economy [Gontard et al., 2018; Michalopoulos et al., 2020; Benabdelkader et al., 2021; Enaime et al., 2024; Fornes et al., 2024; Rezazga et al., 2024; Terribile et al., 2024].

Composting and co-composting of pomace have been the subjects of the greatest research in terms of valorization processes. Organic matter may be stabilized and phytotoxicity reduced by the use of aeration, moisture control, and co-formulation with other biowastes [Alburquerque et al., 2006; Paredes et al., 2005; Tortosa et al., 2012]. Alperujo composts, which are often mixed with other residues, enhance plant nutrition and development [Alburquerque et al., 2007; Muscolo et al., 2019]. This proves that trash may be turned into a resource. Olive grove monitoring over extended periods of time reveals improvements in wettability, structural stability, enzymatic activity, and humic transformation, which are signs of improved biogeochemical functioning Aranda et al., 2015; Aranda et al., 2016; López-Piñeiro et al., 2011].

Using alperujo composts under different watering regimes enhances agronomic and soil-protection indicators at the field size [De Sosa et al., 2023]. This suggests that even in hedgerow systems, reasoned integration may be achieved. According to recent studies conducted on arable crops, they may partly replace mineral fertilizers without reducing yields [García-Rández as al., 2025]. However, when raw alperujo is put directly on the ground, careful measures must be taken to maintain soil quality [Peña et al., 2022; García-Rández et al., 2023]. There seems to be a synergy between biochars and stable organic amendments, since compost or biochar mixtures applied to organic olive orchards over many years improve nutritional status and fertility [Leone et al., 2021; Fornes et al., 2024]. It seems that composting and the "pomace-biochar" approach work well together. Depending on their qualities, biochars may enhance physical attributes, water retention, and porosity [Blanco-Canqui, 2017; Lustosa Filho et al., 2024]. De la Rosa et al., (2022) found that targeted applications in super-intensive olive systems increased soil water status and supported production under managed irrigation. The use of biochars made from pomace reduces the negative effects of salt stress, promotes the development of forage legumes, and enhances certain mechanical and physical characteristics of Vertisols [Gullap et al., 2024; İlay et al., 2025]. But these effects are dose- and pyrolysis-dependent, as well as context-dependent [Kataya et al., 2023; Ammar et al., 2025].

The variety of pomace is a problem that cuts across many areas. The initial composition and "compostability" are affected by factors such as the extraction method (two- vs. three-phase, malaxation, and water content), storage conditions, and mineral fraction [Černe et al., 2023; Ruiz-Castilla et al., 2025]. Modern diagnostic tools, like industrial-scale fluorescence spectroscopy, make it easier to follow transformation trajectories and "humification" [Rueda et al., 2024], which in turn explains variations in stabilization kinetics, phenolic degradation, humic profiles, and agronomic performance. Additionally, the unacknowledged environmental co-benefits of alperujo composts on soil organisms in olive trees [Royer et al., 2023; González-Zamora et al., 2024]. Utilizing indicators of maturity/stability and trace-metal bioavailability, "blend-design" methods that combine pomace with other local organic streams (such as source-separated household biowaste, manures, and prunings) have demonstrated promising fertilizing potential in the Mediterranean region [Doughmi et al., 2022; Doughmi et al., 2023; Doughmi et al., 2024a; Doughmi et al., 2024b; Doughmi et al., 2024c]. Simultaneously, bioindicator invertebrates and target crops are being used to assess fertilizer formulations made from converted pomace for safety and effectiveness [Parri et al., 2024]. Research on germination and other effects of low-dose, long-term ecotoxicity tests supports performance-based safety standards [Javed et al., 2025]. Research by Ruiz-Castilla et al., (2025) and Prakashametla (2006) indicates that gaseous emissions and compostability are affected by biomass storage management at industrial scale. Consequently, techniques for upstream control are needed.

In general, the research agrees that olive pomace, when correctly prepared and preserved, can be used as an amendment to improve structure and water-related co-benefits, as well as to lessen the negative effects of uncontrolled dumping [Tortosa et al., 2018; Kavvadias and Koubouris, 2019]. This review is going to summarize the current knowledge on composting/co-composting processes and the biochar pathway as it pertains to pomace. It will also summarize the agronomic and environmental effects that have been observed in both lab and field settings, talk about the factors that cause variability in extraction and processing, and finally suggest a set of best practices and quality metrics that can be used on a large scale in regions that grow olives [García-Rández et al., 2025; Terribile et al., 2024; Dich et al., 2025].

Search strings combined olive pomace with compost, biochar, soil, humic, germination, enzyme, aggregation, yield, phenolic, salinity, trace metal, bioavailability. This mirrors the search-and-screen logic of the sludge review (databases, dual disciplinary scope, keyword families) [Gontard et al., 2018; Dich et al., 2025; Kataya et al., 2023; Terribile et al., 2024].

Legislation and guidance landscape (framing)

Unlike biosolids – which are directly governed in the EU by Directive 86/278/EEC and complemented by FAO/WHO guidance—olive pomace–derived products typically fall under national fertilizer/soil-amendment frameworks (compost/biochar standards) and waste-to-product end-of-waste criteria. We therefore translate the sludge-review compliance logic to olive pomace: set product specifications (maturity/stability, salinity/EC, pH window, phenolic decline, trace-metal limits/bioavailability) and application controls (dose ceilings vs soil texture/EC and irrigation, timing, monitoring). Adopting the same style of tabulated reference values and quality gates used for biosolids helps align farmer confidence and regulatory readiness [Rezazga et al., 2024; Benabdelkader et al., 2021].

Practical implication: for olive-pomace composts/biochars, publish product labels with EC, pH, GI (germination index), humification indicators, total and available trace metals, and phenolics—plus recommended dose bands and use-cases (soil-structure vs fertility vs hydric stress) [Leone et al., 2021; Peña et al., 2022; Fornes et al., 2024].

Global scenario of olive pomace valorization

Olive pomace (two-phase alperujo and three-phase cake) is increasingly reframed from problematic residue to bioresource within circular bioeconomy agendas. Mature valorization routes now include composting/co-composting with ligno-cellulosic bulking agents to obtain agronomic amendments; biochar production by slow pyrolysis for soil physical/hydric enhancement; and formulated organic fertilizers and soil conditioners derived from stabilized pomace streams [Alburquerque et al., 2006; Tortosa et al., 2012; Blanco-Canqui, 2017; De la Rosa et al., 2022; Parri et al., 2024; Muscolo et al., 2019]. Across Mediterranean contexts, field evidence documents improved soil aggregation, enzymatic activity, and humification after repeated inputs of pomace composts, with positive or neutral effects on yields when doses and maturity criteria are respected [Aranda et al., 2015; Aranda et al., 2016; de Sosa et al., 2023; García-Rández et al., 2025; Fornes et al., 2024]. Recent work adds ecosystem indicators—soil macrofauna responses in olive groves—and operational monitoring tools (fluorescence spectroscopy at plant scale) to steer process quality [González-Zamora et al., 2024; Rueda et al., 2024].

Strong pre-diagnosis and traceability are necessary due to the fact that feedstock heterogeneity, which is caused by factors such as extraction technology, malaxation, moisture, and storage, is a first-order predictor of processability and product performance [Černe et al., 2023; Ruiz-Castilla et al., 2025; Velilla-Delgado et al., 2025]. Based on pyrolysis parameters and agronomic context, biochar derived from pomace may be used to stabilize mechanical components, retain water, and reduce the effects of stress (such as salt and drought) [Gullap et al., 2024; Lustosa Filho et al., 2024; Ammar et al., 2025; İlay et al., 2025].

Moroccan scenario of olive pomace valorization

In Morocco and comparable North-African settings, research and pilot actions converge on co-composting pomace with locally available organics (source-separated household organics, poultry manure, pruning residues) to secure maturity, dilute salinity/phenolics, and deliver plant-available nutrients [Doughmi et al., 2022; Doughmi et al., 2023; Doughmi et al., 2024a; Doughmi et al., 2024b]. Trials report improved germination indices, reduced phytotoxic signatures, and agronomic responses compatible with partial mineral fertilizer substitution when application windows and irrigation are co-managed [Doughmi et al., 2023; de Sosa et al., 2023]. Long-term olive-grove evidence from the wider Mediterranean – wettability, structural stability, enzymatic activity – provides transferable benchmarks for Moroccan pedoclimates [Aranda et al., 2015; Aranda et al., 2016].

Operationally, Moroccan deployments emphasize dose rationalization (≈5–20 t MS·ha^{-1}·an^{-1} for compost) and quality gates (IG ≥80–100%, CE context-adapted, pH 6.5–8.5, declining phenolics, low ETM biodisponibility) prior to field use, with irrigation-aware calendars in arid/semi-arid systems [Alburquerque et al., 2006; de Sosa et al., 2023; Fornes et al., 2024]. New possibilities, such as biochar made from pomace for hydric or structural purposes and synthetic fertilizers, are attracting attention. However, in order to guarantee reliability and inspire trust among farmers, parameterized pyrolysis and labeling frameworks are necessary [De la Rosa et al., 2022; Lustosa Filho et al., 2024; Parri et al., 2024; İlay et al., 2025].

Potential use of olive pomace

When processed correctly, olive pomace becomes a carbon carrier that promotes aggregate stability and microbial functioning, as well as a nutrient vehicle that enhances mineral fertilization. It also contains structural fibers, residual lipids, potassium, and micronutrients [Alburquerque et al., 2007; Aranda et al., 2015; Aranda et al., 2016; López-Piñeiro et al., 2011].

By adjusting C/N, porosity, and aeration, co-composting with nitrogenous or highly structured co-feeds speeds up detoxification (phenolic attenuation) and humification [Paredes et al., 2005; Alburquerque et al., 2006; Leone et al., 2021; Masmoudi et al., 2024]. Depending on factors such as temperature, residence time, and ash content, pomace in biochar form can modulate its hydraulic functionality, mechanical reinforcement, and potential salinity buffering [Blanco-Canqui, 2017; De la Rosa et al., 2022; Lustosa Filho et al., 2024; İlay et al., 2025].

Ecosystem services, such as the enhancement of soil macro-organisms in olive systems and the preservation of soil quality when composting pathways are used instead of direct spreading, contribute to the resource value (González-Zamora et al., 2024; García-Rández et al., 2023). As stated by Rueda et al. (2024), monitoring technologies such as fluorescence spectroscopy and FTIR allow for the tracking of organic-matter changes from process to product, which helps maintain consistent product standards.

Critical synthesis of agronomic performance and risk controls

Olive-pomace amendments can deliver clear agronomic gains, but outcomes depend on product quality at dispatch, site conditions, and application logistics. Across validated programs—compost/co-compost at roughly 5–20 t DM ha^{-1} yr^{-1} and biochar ≤10 t ha^{-1}—studies consistently show rises in soil organic carbon (~0.3–0.8%-points), better aggregate stability (water-stable aggregates up ~10–30%), and higher microbial enzyme activity (~15–40%), with yields generally maintained or modestly increased (+5–15%) under controlled irrigation [Fernández-Hernández et al., 2014; Aranda et al., 2015; Aranda et al., 2016; Royer et al., 2023].

These benefits are strongest on sandy-to-loamy soils and still present – though more gradual – on clay-loams; under deficit or erratic irrigation, compost continues to improve structure and biology while biochar chiefly buffers moisture and salinity stress rather than supplying nutrients [Nogués et al., 2023; Lustosa Filho et al., 2024].

Mechanistically, well-cured composts with high germination index (GI ≥80–100%), suitable pH (6.5–8.5), context-fit EC, reduced phenolics, and low plant-available trace metals minimize phytotoxicity and transient N immobilization, enabling root growth and enzymatic activation; biochar improves pore architecture, water retention, and pH/CEC, and can immobilize certain metals [Alburquerque et al., 2006; Javed et al., 2025; Alburquerque et al., 2009; Doughmi et al., 2024].

Risks concentrate where materials are undercured or saline: high EC or residual phenolics can depress emergence and early vigor, especially in saline-prone settings, which calls for tighter EC specs, split applications, and ensuring a leaching fraction after incorporation [Leone et al., 2021; López-Piñeiro et al., 2011].

In practice, accept only batches meeting the quality gates above, start compost near 5–10 t DM ha^{-1} yr^{-1} in arable systems (8–20 in orchards) and calibrate to texture and salinity; deploy biochar at 2–10 t ha^{-1} when hydraulic buffering is desired [Fernández-Hernández et al., 2014; Royer et al., 2023; Lustosa Filho et al., 2024].

Verify in the field with seasonal pH/EC checks, SOC/WSA trends, enzyme assays where feasible, tissue tests at critical phenophases, and edible-crop safeguards in sensitive contexts; where signals turn adverse—GI <80%, EC elevated, or tissue metals rising—pause or split dosing, extend curing, flush salts, and re-test available metals [Javed et al., 2025; García-Rández et al., 2025; Benabdelkader et al., 2021]. When quality gates are met and monitoring is routine, OP composts and biochars reliably improve soil structure, biological activity, and resilience, translating into neutral to positive yield effects with controlled risk [Fernández-Hernández et al., 2014; Royer et al., 2023].

On sandy-loam to loam soils, OP compost/co-compost at 5–15 t DM ha^{-1} yr^{-1} typically delivers the largest structural and biological gains—WSA often rises 10–30% and enzyme activity 15–40%, translating to neutral-to-positive yield responses under routine irrigation; responses are faster because added organic matter rapidly improves pore continuity and reduces evaporative losses [Aranda et al., 2015; Aranda et al., 2016; Fernández-Hernández et al., 2014]. On clay-loam soils, benefits still accrue but plateau sooner and are sensitive to timing and surface management; higher single doses can accentuate surface sealing if irrigation is uneven, so split applications and shallow incorporation perform better than single, large surface dressings [Royer et al., 2023; Fernández-Hernández et al., 2014].

Compost/co-compost primarily acts through humification, phenolic attenuation, and nutrient supply, which explains stronger effects on early vigor and enzyme activity when GI ≥80–100%, pH 6.5–8.5, and EC is context-fit; under-cured, saline, or phenolic-rich batches can depress emergence and should be deferred or split [Alburquerque et al., 2006; Javed et al., 2025; Alburquerque et al., 2009]. Biochar (≤10 t ha^{-1}) contributes modest nutrient effects but reliably buffers water and salinity stresses, improves pore architecture and pH/CEC, and reduces metal phytoavailability—especially valuable in coarse textures or saline-prone sites; it complements compost by stabilizing structure and smoothing moisture fluctuations rather than replacing nutrient inputs [Nogués et al., 2023; Lustosa Filho et al., 2024; Doughmi et al., 2024].

Under controlled irrigation, validated OP compost programs maintain or improve yields (+5–15% in orchards) while biochar enhances infiltration and water retention; EC tolerances are broader and leaching fractions easier to manage [Fernández-Hernández et al., 2014; Nogués et al., 2023]. Under deficit or erratic irrigation and in saline-prone settings, success depends on tighter product EC limits, split dosing, and ensuring a post-application leaching fraction; without these, high-EC or phenolic carryover can depress emergence and early vigor. Operationally, pair compost with conservative rates and in-season pH/EC checks, and deploy biochar to buffer salinity and drought, especially on sandy–loam soils [Leone et al., 2021; López-Piñeiro et al., 2011; Lustosa Filho et al., 2024]. (Table 1).

Physical-chemical improvement and hydrology

The structural benefits often attributed to olive-pomace (OP) amendments are not linear; they are dose– and texture-dependent saturating responses. On coarse textures, the first 5–10 t DM ha^{-1} typically shifts the pore-size distribution from evaporation-prone micropores toward more meso-/macropores, raising Ks (saturated hydraulic conductivity) and infiltration far more than later increments; beyond ~15–20 t DM ha^{-1}, marginal WSA gains flatten because aggregation becomes C-limited, not dose-limited [Aranda et al., 2015; Aranda et al., 2016].

On clay-loams, early WSA gains are smaller not because the amendment doesn't work, but because microaggregate turnover is governed by clay–Ca bridges and wetting–drying hysteresis; here, a single heavy surface dose can promote crusting if EC or Na is high and irrigation is intermittent, reducing near-surface Ks despite higher total SOC [Fernández-Hernández et al., 2014; Leone et al., 2021]. In calcareous soils, benefits depend on the $CaCO_3$ background: OP compost often stabilizes microaggregates via organo-Ca complexes, but the same carbonate system can buffer pH upward, narrowing micronutrient availability windows (Zn, Fe) unless monitored [Royer et al., 2023].

Biochar is not a generic hydraulic fix, its effect hinges on pyrolysis temperature (≥ 500–600 °C), ash content, and particle size: high-temperature chars increase surface area and water retention but also alkalinity, which helps in acidic/neutral soils yet can over-alkalinize calcareous soils; fine char

Table 1. Recommended field application rates and deployment guidance for olive-pomace compost and biochar

Crop system	Soil texture class	Compost rate (dry matter basis)	Biochar rate (dry matter basis)	Timing and incorporation	References
Olive orchards (conventional or organic)	Sandy to sandy-loam	~5–15 t ha^{-1} yr^{-1}	≤5 t ha^{-1}	Pre-spring or post-harvest; light incorp.; coordinate irrigation & EC	Fornés et al., 2024; Leone et al., 2021
Olive orchards (hedgerow or super-intensive)	Loam to clay-loam	~8–20 t ha^{-1} yr^{-1}	~2–8 t ha^{-1}	Split apps if traffic/ salinity risk; align with fertigation	Leone et al., 2021; De la Rosa et al., 2022
Annual arable crops (for example cereals, legumes)	Sandy-loam to loam	~5–15 t ha^{-1} per rotation	~2–10 t ha^{-1}	Seedbed or post-harvest; adjust mineral N	Fernández-Hernández et al., 2014; Royer et al., 2023
Horticultural crops (open field)	Loam to clay-loam	~10–20 t ha^{-1} between rotations	~2–8 t ha^{-1}	Apply in fallow; allow curing interval before sensitive crops	Fernández-Hernández et al., 2014; Royer et al., 2023
Soil rehabilitation or degraded sites	Any texture	Case by case	Case by case	Under site plan; manage leachate/ erosion	Enaime et al., 2024

(<0.5 mm) can clog pores in silty topsoils and lower infiltration if incorporated shallowly [Nogués et al., 2023; Lustosa Filho et al., 2024]. Finally, irrigation water quality is a hidden moderator: sodic water (high SAR) can undo aggregation gains even with good compost, so hydrologic improvements should be interpreted with concurrent water chemistry [Leone et al., 2021]. (Table 2).

Nutrient behavior, salinity, and soil chemistry under real field variability

Claims of nutrient supply from OP compost blur a critical timing issue: the N immobilization window. With C/N typically >15–20, many OP composts create a 2–6 week drawdown in mineral N after application; yields are stable where

Table 2. Product specifications and quality gates for olive-pomace compost and biochar before field application

Parameter	Target or acceptable range	Why it matters	References
Germination index (using a sensitive test species)	At least 80 to 100 percent	Screens for residual phytotoxic compounds and excessive salinity that depress seedling emergence and early growth	Alburquerque et al., 2006; Javed et al., 2025
Potential of hydrogen (pH)	6.5 to 8.5 (context dependent)	Influences nutrient availability, metal mobility, and soil biological activity	Leone et al., 2021; Fornés et al., 2024
Electrical conductivity (salinity)	Context adapted; typically low to moderate for orchard and arable soils	High salinity inhibits germination and root growth and can worsen osmotic stress in dry climates	Fornés et al., 2024; Leone et al., 2021
Phenolic compounds (total extractable)	Declining trend compared with feedstock; low residual levels	Fresh pomace contains phenolics that are phytotoxic; composting and curing should reduce them	Alburquerque et al., 2006; Fernández-Hernández et al., 2014
Stability and maturity (respiration or carbon dioxide evolution)	Low respiration rate; evidence of stable organic matter	Ensures the material will not immobilize nitrogen or heat up after application	Fernández-Hernández et al., 2014; De Sosa et al., 2023
Hygiene (where relevant)	Absence of target indicator organisms; verified temperature history	Protects workers, soil, and crops from biological hazards	Javed et al., 2025
Trace metals (total and plant-available fractions)	Within national or internationall limits; low plant-available fractions	Limits environmental risk and food-chain transfer	Doughmi et al., 2024; Benabdelkader et al., 2021
Moisture content (for compost)	About 30 to 50 percent at dispatch	Affects handling, spreading, and further biological activity	Fornés et al., 2024; Fernández-Hernández et al., 2014
Biochar basic properties (for biochar products)	Declared production temperature and holding time; ash content; surface area; potential of hydrogen; basic hydraulic indicators	Links the product to intended soil functions (water retention, structure, salinity buffering)	De la Rosa et al., 2022; Fornés et al., 2024

irrigation/fertilization buffer that trough, but seedbed systems can show measurable vigor penalties if this window overlaps emergence [Alburquerque et al., 2006; Javed et al., 2025]. For P and K, positive responses are common in P-fixing and K-poor soils, yet the magnitude is strongly controlled by Fe/Al oxide content and exchange phase – in Fe-rich topsoils the available P bump can be transient, collapsing as organic ligands mineralize [Fernández-Hernández et al., 2014; Royer et al., 2023]. Biochar's contribution is indirect: increased CEC, pH modulation, and sorption sites lower temporal variance in nutrient availability rather than raising mean levels; this is why char often stabilizes yields under stress while showing small mean yield gains [Nogués et al., 2023].

Salinity is not a single number, the EC thresholds differ by extract method (1:5 vs. saturation paste) and by crop and phenophase. The same compost EC that is benign for woody perennials in winter can be damaging in spring for germinating annuals at the same site. Residual phenolics compound osmotic stress: Folin–Ciocalteu (F–C assay) total phenolics and GI do not always align because Folin quantifies reducing capacity, not specific phytotoxins [Alburquerque et al., 2009; Javed et al., 2025]. This means GI ≥ 80–100% is necessary but not sufficient where irrigation salinity and evaporative demand are high; salt load (kg ha^{-1}) and ionic composition (Na/Cl) matter more than EC alone [Leone et al., 2021; López-Piñeiro et al., 2011]. (Table 3).

Factors influencing microbial community dynamics and biological functioning

Olive-pomace composting follows a thermally driven ecological sequence. During the thermophilic phase, spore-forming Bacilli and many Actinobacteria dominate; as temperatures decline and curing begins, communities diversify toward mesophilic bacteria and fungi. This succession parallels the attenuation of aromatic and phenolic compounds and the emergence of oxidative catalysts – laccases, peroxidases, multicopper oxidases, and ring-cleaving dioxygenases – that enable depolymerization and mineralization of complex substrates [Aranda et al., 2015; Aranda

Table 3. Monitoring and verification plan for fields receiving olive-pomace–derived amendments

Indicator to monitor	Sampling depth or stage + Frequency and duration	Expected trend (validated inputs)	Interpretation and corrective actions	References
Soil potential of hydrogen	0–20 cm; baseline + each season	Stay in crop window	Adjust dose/timing; amendments as needed	Fernández-Hernández et al., 2014; De Sosa et al., 2023
Soil electrical conductivity (salinity)	Topsoil; sensitive stages	Stable/moderate, < crop limit	Reduce rate, increase leaching, reschedule	Fernández-Hernández et al., 2014; De Sosa et al., 2023
Organic carbon and particulate organic matter	Annual, same season	↑ or maintained	Revisit dose, incorporation, residues	Fernández-Hernández et al., 2014; De Sosa et al., 2023
Water-stable aggregate percentage and bulk density	Annual	↑ stability; ↓ density	Add biochar or raise compost rate	Aranda et al., 2015; Fornés et al., 2024
Soil enzyme activities (for example dehydrogenase, β-glucosidase)	Annual / Biannual	↑ vs baseline	Recheck maturity/ phenolics	Alburquerque et al., 2006; Fernández-Hernández et al., 2014
Extractable phenolic compounds in soil	Early post-application + mid-season	Low, declining	Delay sensitive crops, extend curing, lower rate	Alburquerque et al., 2006; Fernández-Hernández et al., 2014
Plant tissue nutrients (leaf diagnostics)	Crop stage-specific	In sufficiency range	Adjust mineral fertilization	Peña et al., 2022; Fernández-Hernández et al., 2014
Crop performance (emergence, biomass, yield, product quality)	Each season	Neutral to ↑	Verify quality gates; tweak rate/timing	Fernández-Hernández et al., 2014; De Sosa et al., 2023
Soil fauna and bioindicator responses	Baseline + annual	Neutral to ↑	Retest product; pause until resolved	Bhaduri et al., 2022
Trace metals in soil and edible	Baseline; 1–3 seasons	Stable within limits	Cut rates; reassess sourcing	Doughmi et al., 2024; Benabdelkader et al., 2021

et al., 2016; Innangi et al., 2017]. Yet much of the literature still infers function from taxonomic co-occurrence: increases in the relative abundance of Actinobacteria are often cited as evidence of ring cleavage, and short-lived peaks in "laccase activity" are taken as proof of sustained expression. These inferences are tenuous because amplicon surveys describe community composition in relative terms, not absolute abundance or metabolic activity, and single time-point enzyme assays are highly sensitive to moisture and temperature at sampling [Javed et al., 2025].

Community assembly is governed by a blend of deterministic filters and stochastic events. Deterministic filters include the temperature envelope and cumulative time at high temperature, oxygen supply provided by turning or forced aeration, moisture held near optimal water-holding capacity, progressive drift in pH, the background of soluble salts, and the carbon-to-nitrogen ratio of the blend. Stochastic forces include priority effects introduced with bulking agents, immigration from irrigation water and air, and top-down control by protists and bacteriophages. As a result, nominally similar feedstocks can diverge when aeration geometry or turning cadence differs, because oxygen heterogeneity selects distinct thermophiles and favors alternative pathways of degradation. Elevated salinity and residual phenolics also act as directional stressors: they select osmotolerant, fast-growing heterotrophs, suppress arbuscular mycorrhizal fungi and sensitive nitrifiers, and can yield communities with high potential activity but low functional evenness unless stress is relieved during curing [Aranda et al., 2016; Javed et al., 2025].

Amendment design can stabilize or destabilize these trajectories. Co-application of biochar often moderates moisture, pH, and redox microhabitats and can protect extracellular enzymes from denaturation, sustaining activity during dry spells. Outcomes, however, depend on pyrolysis temperature, ash content, and particle size. Very fine or high-ash materials can coat reactive surfaces and reduce aeration in the near-surface layer, dampening nitrification and early colonization by arbuscular mycorrhizal fungi. In contrast, moderate-sized particles produced at higher temperature tend to buffer pH and provide refugia for oxidative consortia, which can hasten phenolic turnover, although excessive alkalinity in calcareous soils may narrow the availability of micronutrients after land application [Innangi et al., 2017].

Advancing beyond correlation requires explicit causal chains that link genes, transcripts, enzymes, substrates, and field performance. A credible approach combines enzyme-resolved metagenomics and metatranscriptomics targeted at laccase, peroxidase, and dioxygenase families with standardized extracellular activity assays that control for temperature and moisture. Absolute microbial abundance should be tracked through quantitative polymerase chain reaction, fumigation–extraction of microbial biomass carbon, phospholipid fatty acid analysis, or direct cell counts so that community shifts are not merely denominator effects. The substrate landscape must be measured directly. The Folin–Ciocalteu assay provides a rapid index of reducing capacity but is not specific for phenolics; it should be complemented with targeted chromatographic profiles of key olive phenolics such as hydroxytyrosol, tyrosol, and oleuropein, and, where relevant, polycyclic aromatic hydrocarbon panels. Where feasible, stable-isotope probing with labelled phenolics or RNA stable-isotope probing, together with bioorthogonal non-canonical amino acid tagging and fluorescence-activated cell sorting, can separate truly active degraders from dormant passengers and thereby confirm causality between consortia and substrate turnover [Aranda et al., 2016; Innangi et al., 2017; Javed et al., 2025].

In practice, process control is the fastest route to better microbial outcomes while the molecular toolkit matures. During the hot phase, maintaining adequate oxygen through forced aeration or tighter turning and holding moisture near optimal water-holding capacity prevents anoxic pockets, thermal collapse, and the formation of odorous intermediates. During curing, deliberate reduction of soluble salts and stabilization of pH widen the niche for arbuscular mycorrhizal fungi and nitrifiers and shift communities from dominance by fast-growing bacteria toward more even, functionally diverse consortia that better predict field performance. At release, acceptance criteria should include a germination index in the non-phytotoxic range, electrical conductivity appropriate for the receiving soil and irrigation context with the analytical method stated, a downward trend in targeted phenolics, and evidence of oxidative capacity from a standardized assay [Aranda et al., 2015; Aranda et al., 2016; Javed et al., 2025].

Risk, monitoring, and implementation at scale

Programs often falter for reasons that are both predictable and avoidable because materials that have not fully cured or that retain high phenolic loads are sometimes applied during the most sensitive crop stages, and single heavy doses are broadcast on saline-prone or fine-textured topsoils without an immediate leaching fraction. Failures also arise when electrical conductivity is measured with one laboratory method while field planning assumes thresholds from another, and when managers treat total trace metals as a proxy for agronomic safety even though plant-available fractions govern uptake. The mechanisms are straightforward since residual phenolics and salts impose osmotic and oxidative stress on germinating tissues, heavy surface dressings encourage crusting and near-surface hydraulic failure in clay-rich horizons, method drift for electrical conductivity and for the germination index obscures true exposure, and totals can misclassify hazard relative to availability assays that reflect real uptake risk [Alburquerque et al., 2009; López-Piñeiro et al., 2011; Leone et al., 2021; Doughmi et al., 2024; Javed et al., 2025].

Monitoring adds value only when it targets these specific failure points and when every measurement implies a management action. The product should therefore be screened before application so that the germination index is clearly non-phytotoxic, the electrical conductivity value is reported together with its analytical method, the targeted phenolic profile is trending downward, and the plant-available metals fall within crop and soil limits. The field should likewise have a short baseline for soil reaction, electrical conductivity measured with the same method, organic carbon, and a structural indicator such as water-stable aggregates. Two to three weeks after application, managers should remeasure topsoil electrical conductivity with the same method and pair this result with a simple tissue nitrogen reading in sensitive crops because this is the window when the combination of nitrogen immobilization and salt load most often depresses vigor. At a critical phenophase, tissue analysis should be repeated and, where edible crops are grown in higher-risk contexts, an edible-part check should be added. After harvest, organic carbon, structural stability, and a single enzyme such as beta-glucosidase provide evidence that biological and structural gains are consolidating rather than merely spiking with short-lived moisture pulses [Aranda et al., 2016; García-Rández et al., 2025; Javed et al., 2025].

Scaling shifts the central problem from achieving a good mean response to controlling variance because lot-to-lot heterogeneity in feedstocks, curing, and storage widens the distribution of outcomes as volumes grow. Variance narrows when procurement requires certified lots that report the germination index, the electrical conductivity value together with the method, pH, the phenolic method and value, plant-available metals, and curing age, and when receivers spot-check arrivals, store under cover to prevent re-contamination, and maintain a simple dashboard that visualizes deviations in soil electrical conductivity as well as tissue or edible-part flags. In regions where water scarcity or salinity volatility is high, pairing compost with biochar reduces yield variance even when average gains are modest because the combination buffers salinity and drought, which is economically rational for risk-averse growers in arid environments [Nogués et al., 2023; Fernández-Hernández et al., 2014].

CONSTRAINTS

Feedstock heterogeneity begins at the mill and continues during storage, which means that phenolic load, salinity, and biodegradability can swing widely with extraction technology, malaxation settings, added water, and holding conditions. These shifts do not simply change averages; they alter the kinetics of composting and the ability of oxidative consortia to detoxify the matrix, so two visually similar batches can behave very differently once windrowed. Evidence from recent processing studies shows that water addition and longer storage promote leachate formation and secondary reactions, which then affect both the rate of temperature rise and the quality of the cured product [Černe et al., 2023; Ruiz-Castilla et al., 2025; Velilla-Delgado et al., 2025]. The practical implication is that programs should classify incoming olive residues by process provenance and age rather than treating all pomace as a single material stream.

Phytotoxicity and salinity remain the most immediate agronomic hazards because immature or saline materials suppress germination and early growth even when total nutrient contents look favorable. The simple safeguard is to screen for maturity and ionic strength before land application.

Batches should meet a germination index in the non-phytotoxic range that is to say at least eighty to one hundred percent, should present electrical conductivity values appropriate for the receiving soil and irrigation water, and should fall within a product pH window of roughly six and a half to eight and a half while targeted phenolics decline during curing. Where these conditions are not met, early vigor penalties are likely and the risk rises sharply for seedbeds and edible crops [Alburquerque et al., 2006; de Sosa et al., 2023; Doughmi et al., 2023]. Programs that insist on method disclosure for the germination index and for electrical conductivity avoid many misclassifications because thresholds depend on how the test was run.

Process control becomes harder as volumes grow, therefore standard operating procedures and operational monitoring are not optional but central. Aeration and moisture must be managed to sustain repeated thermophilic cycles and to prevent anoxic pockets, while temperature records should demonstrate sufficient time at high temperature to assure hygiene. In practice the industrial bottlenecks are logistical rather than biological, since windrow geometry, traffic patterns, and stormwater handling drive odor, leachate generation, and lot cross-contamination. Facilities that document maturity with consistent indices and that separate curing from finished storage experience fewer field failures than those that rely on visual cues alone [Rueda et al., 2024; Leone et al., 2021; Velilla-Delgado et al., 2025].

Context dependence means that dose and timing cannot be universal, because climate, irrigation regime, and soil texture determine both risk and payoff. On coarse soils under controlled irrigation, compost additions can be bolder, whereas on clay-loams or in saline-prone settings the same single surface dose may raise near-surface salinity and promote crusting unless applications are split and followed by a leaching fraction. Where rainfall is erratic or water quality is sodic, even compliant materials should be scheduled away from sensitive phenophases and paired with field verification of topsoil electrical conductivity and tissue nitrogen soon after application. Trials in orchards and annual systems confirm that local calibration of rate and timing reduces transient nitrogen immobilization and osmotic stress while preserving the structural and biological gains that motivate adoption [Aranda et al., 2016; de Sosa et al., 2023; Fornés et al., 2024; Peña et al., 2022].

Knowledge and labeling gaps continue to slow safe scaling. Farmers and advisers do not only need recommendations about biochar manufacture such as pyrolysis temperature and ash content; they also need product-level criteria printed on each lot so that maturity, electrical conductivity with method, pH, targeted phenolics, and the bioavailability of trace elements are visible at purchase. Without this information, risk management collapses into guesswork and lot-to-lot variability turns into crop-to-crop variability. The recent literature converges on the same conclusion, which is that practical adoption improves when labels link material properties to intended use and when buyers can match those properties to their soils and crops [Blanco-Canqui, 2017; Lustosa Filho et al., 2024; İlay et al., 2025; De la Rosa et al., 2022].

Environmental safeguards require the same discipline. Direct land spreading of raw pomace threatens soil structure and biota, whereas stabilized products such as compost and biochar reduce hazard and deliver more consistent outcomes. Even stabilized materials demand attention to emissions and leachates during processing, since poor pad design and runoff control can externalize impacts to water bodies. Field-facing ecotoxicity checks add an essential layer because germination assays and simple soil-fauna indicators reveal lingering toxicity that bulk chemistry can miss. Programs that couple process hygiene with seasonal bioassays are better at catching outliers and preventing long memory effects in soil communities [García-Rández et al., 2023; Javed et al., 2025; González-Zamora et al., 2024; Peña et al., 2022; Sajdak et al., 2025].

CONCLUSIONS

Our aim was to judge whether olive-pomace amendments can be used safely and effectively, and to turn scattered findings into field rules. That aim was achieved. We show that mature composts and co-composts within context-appropriate rates, together with biochar used for stress buffering, improve soil structure, organic carbon, and biological functioning while keeping yields stable or modestly higher under managed irrigation. The review adds three things that were missing from the literature: batch-release quality gates that make product safety testable in practice, rate and timing guidance that depends on soil texture and irrigation rather than one-size advice, and a lean monitoring cadence where each measurement triggers a management action. This closes the implementation gap between policy intent and on-farm decisions.

Limits remain because reporting of electrical conductivity, germination index, and phenolics is inconsistent and biological evidence often relies on proxies. The next steps are straightforward: standardize labels and procurement checks, run multi-season trials that resolve dose–response by context with plant-available metals and targeted phenolics, and advance causal microbiology to explain why some curing paths succeed faster.

A final prospect emerges for practice and policy. The framework can be adopted immediately by growers, advisors, and regulators because it links product labels to placement decisions and to simple field checks that are feasible at scale. As quality gates and monitoring become standard, supply chains will converge on safer, faster-curing materials, and programs can prioritize co-application strategies that reduce yield variability under water and salinity stress while advancing circular-economy goals. This creates a clear path from pilot successes to region-wide adoption with measurable soil and crop benefits.

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