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Field Application and Effect Evaluation of Biological Control Measures in *Chrysanthemum morifolium* (Hangbaiju)

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Abstract Hangbaiju (*Chrysanthemum morifolium* Ramat. cv. 'Hangbaiju') is both a traditional specialty crop and an edible, flower-based product whose market value depends on aesthetics, aroma, safety, and consumer trust. In many production bases, pest and disease pressure is increasing and is amplifying the tension between yield protection and residue-reduction goals. Chemical control often provides rapid suppression, but repeated use can destabilize greenhouse or field agroecosystems, erode beneficial microbial and arthropod communities, and raise social and regulatory concerns-especially for a flower that is harvested and directly infused as tea. This study synthesizes recent evidence on biological control technologies relevant to Hangbaiju production, with emphasis on what is practical in field deployment rather than what works only in controlled laboratory settings. The scope covers (i) microbial-based tools, including antagonistic bacteria/fungi and plant growth–promoting rhizobacteria; (ii) botanical pesticides and plant-derived insecticides; and (iii) utilization of natural enemies, with both augmentative releases (where feasible) and conservation biological control (habitat and resource management). This study then evaluates reported field/production-scale outcomes using comparable endpoints such as disease or pest suppression, stability across time, compatibility with cultivation operations, and likely economic implications, while avoiding any fabricated datasets. A case-driven synthesis is built around two documented problem windows in Hangbaiju systems: the bloom-stage contamination risk from chrysanthemum aphids (Macrosiphoniella sanborni) and the recurring soil-borne wilt complex affecting chrysanthemum production. The evidence consistently suggests that integrated approaches—especially those combining preventive microbial inputs, selective botanicals, and strategies that protect or enhance natural enemies—tend to outperform single-method interventions in robustness and practical adoptability.
Keywords *Chrysanthemum morifolium*; Biological control; Field application; Effect evaluation; Green agriculture

1 Introduction

Hangbaiju is formally recognized and standardized as a geographical-indication product in China, reflecting its strong geographic branding and the expectation of consistent quality attributes in commercial trade. Beyond branding, the production system itself shapes management choices. Hangbaiju is one of the traditional specialty and advantageous agricultural products in Tongxiang City, Zhejiang Province, with a cultivation history spanning over 300 years. The annual planting area covers approximately 3300 ha, yielding an annual output of 6,000 tons (Figure 1). A field survey summarized in a recent Frontiers dataset paper notes that Tongxiang City (Zhejiang Province)—the origin region frequently associated with Hangbaiju—tied to the flower stage linked with optimal medicinal or product properties. This concentrated harvest period magnifies the operational impact of late-season pests and quality defects: problems that would be manageable with flexible harvest scheduling become high-stakes events when harvest labor and processing capacity are already strained (Zang et al., 2023).

In practical terms, Hangbaiju's "economic value" is not only yield-per-area but also saleability: flower integrity, visual cleanliness, and consumer experience. A distinctive example is the bloom-stage aphid problem: Macrosiphoniella sanborni adults and bodies can remain with harvested flowers and become visible in the tea infusion, causing consumer rejection ("off their appetite" in the English abstract). This is a quality pathway that is unusual for many other crops, and it strongly incentivizes growers to seek control methods that work specifically during bloom without compromising harvest safety or market access (Cao et al., 2024).

Figure 1 Hangbaiju production base of Tongxiang Lvkang Chrysanthemum Industry Co., Ltd. (Photo by Weiying Gao)

The broader chrysanthemum production landscape (including ornamentals and edible/tea chrysanthemums) faces an expanding list of pathogens and pests, and recent reviews emphasize that control challenges are not only biological but also technological: improved diagnostics are identifying cryptic species complexes and mixed infections that earlier management models treated as one disease. For example, the 2015–2025 synthesis of chrysanthemum pest/disease research stresses that fungal, bacterial, viral, and insect problems remain major drivers of yield and quality losses, while new molecular and ecological tools are reshaping both detection and control strategies (Chen et al., 2025).

For Hangbaiju specifically, two pest situations stand out in the accessible Tongxiang-focused literature. First is bloom-stage aphid infestation and contamination risk from M. sanborni, which is explicitly described as feeding on or hiding within flowers and being carried through harvest and processing. Second is the soil-borne/wilt complex that can cause plant loss and reduced stand vigor, and in some studies is linked to Fusarium incarnatum rather than the historically assumed Fusarium oxysporum forma specialis. These are not marginal issues: they are framed in the reviewed studies as drivers of significant losses or high management pressure (Cao et al., 2024).

Chemical control remains a dominant tool in many chrysanthemum production systems because it is fast, familiar, and often initially effective. Yet several limitations matter more sharply in Hangbaiju than in purely ornamental markets. First, consumers ingest Hangbaiju as an infusion, so the “edible flower” identity makes residue anxiety and risk perception more central; even when legal residue limits are met, visible or sensory signs of intensive pesticide use can damage market trust. Second, repeated chemical inputs can disrupt beneficial microbes and the ecological functions that support plant health; a greenhouse study on microbial inoculants in cut chrysanthemum explicitly notes that chemical control is common but “not environmentally friendly” and can have “negative effects on beneficial microbes” (Wang et al., 2024). Third, pesticide resistance and the behavioral ecology of pests can erode chemical performance. Thrips are a classic example: the chrysanthemum–thrips study using soil-dwelling predatory mites frames chemical control as difficult partly because thrips have a short generation time, can evade sprays, and can develop pesticide resistance, motivating a shift toward IPM and biological control. Finally, chemical programs often struggle with bloom-stage constraints. In Hangbaiju, bloom is not just a biological stage but also the commercial product stage: interventions must preserve flower quality and minimize contamination. When chemical sprays are used late, they can collide with harvest scheduling, pre-harvest intervals, and the practical challenge of keeping harvested flower material “clean” in both residue and appearance. This is one reason why control methods that are physically targeted (e.g., traps) or biologically selective (e.g., compatible botanicals, microbial antagonists, or natural enemies) have become more attractive in research and extension narratives (Cao et al., 2024).

Across chrysanthemum research in the last decade, biological control is no longer treated as a niche alternative but increasingly as a main pillar of sustainability-oriented production systems. The large 2015–2025 review explicitly lists biocontrol agents-Trichoderma spp., Bacillus spp., predatory mites, and entomopathogenic fungi—as demonstrated tools and argues for future integration with microbiome management, molecular breeding, and RNA-based tools to achieve more durable control (Chen et al., 2025).

At the microbial-technology frontier, two developments are especially relevant for Hangbaiju growers and extension teams. One is the move from single strains to compatible consortia and co-inoculations. An open-access review in *Biological Control* argues that co-inoculations of Trichoderma with beneficial bacteria (often Bacillus or Pseudomonas) can produce synergistic benefits, and highlights that formulation and compatibility are central steps if such synergy is to translate outside the lab (Poveda and Eugui, 2022). The second development is the more explicit coupling of "biocontrol" with "plant growth and quality." A greenhouse study on co-inoculation of Bacillus velezensis and Pseudomonas aeruginosa in chrysanthemum reports improvements in growth and quality relative to single-strain inoculation, while also pointing to induced defense and immune activation (e.g., upregulation of defense-related transcription factors) as part of the mechanism. This matters for Hangbaiju because quality parameters—flower integrity, harvest timing, and market acceptance—are tightly linked to both stress and disease pressure (Wang et al., 2024).

This study has two practical objectives. The first is to summarize the biological control technologies most relevant to Hangbaiju cultivation, with attention to what is actually deployable under field constraints—timing, labor, weather, bloom-stage restrictions, and the economics of repeated applications. The second is to evaluate field application effects using traceable published evidence, focusing on comparative suppression of pests/diseases, yield and quality implications where reported, and practical performance compared to conventional chemical programs.

2 Major Pests and Diseases and Control Requirements in Hangbaiju

2.1 Major diseases and their characteristics

Hangbaiju disease management is best understood as a set of "risk windows" rather than a static list. Soil-borne diseases (wilt, root rots, blights under continuous cropping or soil fatigue) tend to build over time and intensify when production becomes more intensive, while foliar diseases fluctuate with weather, canopy density, and late-season management. The broad chrysanthemum review for 2015–2025 emphasizes that fungal pathogens cause leaf spot, wilt, rust, blight, and rot, affecting both yield and quality, and that improved molecular identification is changing how these diseases are classified and managed (Chen et al., 2025).

A key disease point that is directly relevant to Hangbaiju biological control is the wilt complex linked to Fusarium. The Hangbaiju-focused study in the Chinese Journal of Biological Control identifies the wilt pathogen for chrysanthemum as Fusarium incarnatum based on morphological and ITS sequence analysis, highlighting that "Fusarium wilt caused huge yield loss" and framing accurate identification as the foundation for effective control. This is important for practice: if the pathogen is misidentified, chemical or biological choices can be mismatched, leading to costly failures.

For Hangbaiju leaf and flower quality, foliar disease pressure is also significant, but accessible open literature in this query is more detailed on insect contamination than on leaf-spot epidemiology within Tongxiang fields. In such cases, a practical review approach is to focus on biological-control principles that are robust across multiple foliar pathogens—preventive microbiome support, canopy microclimate management, and the use of antagonists with broad-spectrum suppression—rather than overfitting recommendations to one pathogen that may not be uniformly dominant across production bases (Chen et al., 2025).

2.2 Major insect pests and their damage patterns

The insect damage profile of Hangbaiju has one unusual, market-critical feature: pests can directly contaminate the harvested flower product. The bloom-stage aphid case is the clearest example. Cao and colleagues describe M. sanborni as feeding on flowers and hiding within them, then being harvested and remaining in processed chrysanthemum-tea products; when flowers are brewed, aphid bodies can float in the tea, causing consumer disgust and product rejection. This connects entomology to quality control more directly than in many crops, and it explains why field control requirements must include "harvest cleanliness," not only reduction of feeding damage (Cao et al., 2024).

Thrips represent another common chrysanthemum pest group, with damage patterns that complicate chemical control. In a greenhouse chrysanthemum trial, the authors describe thrips control as difficult because of thrips' behavioral avoidance, rapid generation time, and pesticide resistance development. Importantly, thrips have a life cycle phase in the soil, creating an opportunity for soil-dwelling natural enemies that do not rely on perfect spray coverage of foliage. At the broader "chrysanthemum as a crop" level, recent reviews also emphasize aphids and thrips as key pests with virus-vector potential and highlight the role of resistance traits (trichomes, terpenoids, lignin) and biological control agents (predatory mites, entomopathogenic fungi) in sustainable management. While Hangbaiju's production ecology differs from greenhouse ornamentals, these findings still shape technology options and selection criteria (Chen et al., 2025).

2.3 Challenges in field control

Field control in Hangbaiju is constrained by three interacting realities. First, the harvest window is narrow and often labor-limited, so any late-season pest or disease flare-up can translate into either harvest delays (missing the optimal flower stage) or quality downgrades. The Tongxiang-focused survey cited by Zang and colleagues explicitly notes a harvest period "usually lasts 25 days," and also points to the difficulty of recruiting many trained farmers in a short time, a labor constraint that matters for repeated spray-based control programs (Zang et al., 2023).

Second, bloom-stage interventions must avoid harming the marketable organ. The aphid contamination pathway illustrates how bloom-stage spraying can be simultaneously necessary (for pest control) and risky (for product safety and market perception). Methods that physically remove or intercept pests (e.g., attractant-baited sticky traps) become attractive because they can be deployed during bloom with less direct chemical exposure to the harvested flowers (Cao et al., 2024).

Third, sustained field efficacy depends on ecological stability. Biological control is often more sensitive to microclimate and agronomic practices than "spray-and-kill" approaches, but chemical approaches can destabilize beneficial communities and create rebound pest problems. In modern chrysanthemum research, this has led to a pragmatic middle position: biological control is most robust when it is preventive and integrated, rather than used as a single replacement input (Serrão et al., 2024).

3 Types and Application Progress of Biological Control Technologies

3.1 Microbial-based control technologies

In Hangbaiju systems, microbial-based control is best seen as a spectrum of tools rather than a single category. At one end are classic antagonists that directly inhibit pathogens through antibiosis, competition, and enzymatic degradation; at the other end are plant growth–promoting rhizobacteria (PGPR) that reshape nutrient use efficiency and trigger immune activation, thereby increasing tolerance and reducing the effective damage from disease pressure. The chrysanthemum co-inoculation study by Wang et al. (2024) and colleagues explicitly frames PGPR inoculation as a sustainable strategy and reports that co-inoculation increased plant nutrient absorption/utilization and improved growth and quality relative to single inoculation; transcriptome results also indicate upregulation of defense and signaling pathways, implying that the "control effect" is partly mediated through induced resistance rather than only pathogen suppression.

For disease control at a higher evidence level across crops, a 2024 meta-analysis of Bacillus-based biocontrol reports that Bacillus agents reduced disease by about 60% compared to negative controls in the compiled literature. The same meta-analysis highlights two practice-relevant principles: higher inoculum concentrations tend to yield stronger protective effects, and protective (preventive) inoculation generally outperforms therapeutic use after disease establishment. These findings map directly onto Hangbaiju field realities: if application is delayed until symptoms surge near harvest, biological control often appears "unstable," but when microbial tools are integrated earlier as preventive management, performance is more reliable (Serrão et al., 2024).

A Hangbaiju-specific microbial-control example is the use of Streptomyces diastatochromogenes 1628 metabolites against Fusarium-associated wilt. In the Chinese Journal of Biological Control report, metabolites of *S. diastatochromogenes* 1628 were tested against *Fusarium incarnatum* (identified as the pathogen), with pot-trial results reporting both protective and therapeutic effects after 14 and 28 days, with protective efficacy higher than therapeutic efficacy. This pattern aligns with the broader meta-analysis conclusion that preventive use tends to be stronger than "curative" use once disease is established.Technologically, the field is also moving toward multi-microbe or consortium approaches. Poveda and Eugui argue that Trichoderma–bacteria co-inoculations can produce synergistic benefits, sometimes approaching chemical-pesticide outcomes, but they emphasize formulation and compatibility as key steps for real-world adoption. For Hangbaiju, this highlights a practical boundary: the most promising microbial agents are not always the most deployable unless they are formulated for local transport, storage, and farmer-friendly application schedules (Poveda and Eugui, 2022).

3.2 Botanical pesticides

Botanical pesticides occupy a strategic middle ground for Hangbaiju: they can reduce reliance on broad-spectrum synthetics while maintaining the operational simplicity of spray-based programs. Yet botanical pesticides are not inherently "weak"; the best ones have distinct modes of action and can be embedded into IPM programs as selective tools.

Azadirachtin (from neem) is one of the most globally recognized botanical insecticides. In a 2021 review, it is characterized as a potent antifeedant and insect growth disruptor with low residual power and relatively low toxicity to many biocontrol agents, predators, and parasitoids, a profile that fits integrated programs where natural enemies are valued rather than collateral damage. The same review also notes practical limitations, including stability and the need for strategies (including formulation innovations such as nano-enabled delivery) to control release rate and improve field persistence (Kilani-Morakchi et al., 2021).

Evidence from chrysanthemum-focused trials shows that plant extracts can achieve meaningful suppression of aphids under protected cultivation. In a 2024 study evaluating several botanical insecticides against *Aphis gossypii* on chrysanthemum (plastic house conditions), the extract of *Chrysanthemum cinerariaefolium* at 3.0 and 3.5 g/L achieved reported average efficacy values of 76% and 72%, respectively, and was described as the most consistent treatment among those tested. This is important for Hangbaiju because it illustrates a realistic control magnitude for botanicals—strong enough to be operationally relevant, especially when combined with monitoring, sanitation, and conservation biological control (Hutapea et al., 2024).

Botanical tools also connect to the chrysanthemum plant's own defense chemistry. Research on pyrethrum flowers shows that producing aphid alarm pheromone can repel herbivores and recruit carnivores, illustrating how plant-derived signals and compounds can function simultaneously as direct defense and as ecological regulation. While pyrethrum is not Hangbaiju, the principle is transferable: integrated programs can combine plant-derived chemistry, physical trapping, and natural enemies without relying on a single "silver bullet" insecticide (Hutapea et al., 2024).

3.3 Utilization of natural enemies

Natural-enemy utilization in chrysanthemum production spans augmentative release (adding commercially produced natural enemies) and conservation biological control (managing habitats, nectar resources, refuges, and pesticide selectivity to sustain resident enemies). Hangbaiju is largely field-grown, which can make repeated augmentative releases less predictable than in controlled greenhouses; nonetheless, greenhouse studies still provide valuable mechanistic guidance for timing and target life stages.

A clear example of natural-enemy utility is the greenhouse chrysanthemum trial using the soil-dwelling predatory mite *Stratiolaelaps scimitus*. The study describes thrips as difficult to control with chemicals and reports that releases of *S. scimitus* (using a farmer self-production approach) reduced thrips density substantially, with the treated greenhouse showing 74.9% suppression relative to the untreated greenhouse by late September (2018). The authors explicitly interpret this as evidence that soil-dwelling predators can suppress the thrips stage that drops to soil for pupation, an approach that complements foliage-based measures and reduces reliance on repeated sprays.

For Hangbaiju, an equally important natural-enemy concept is "making the field hospitable" to predators and parasitoids. The bloom-stage aphid paper itself highlights that visual and olfactory cues can be leveraged to attract pests into traps; by analogy, ecological regulation can be used to enhance natural-enemy foraging and persistence through habitat features and resource provisioning. In practical IPM, this typically means preserving nectar resources, avoiding broad-spectrum sprays during peak enemy activity, and ensuring that field sanitation removes pest reservoirs without eliminating beneficial refuges (Cao et al., 2024).

3.4 Integrated biological control strategies

In my view, the central question for Hangbaiju is not whether biological control "works," but which integration pattern makes it reliable when weather, labor, and market timing are non-negotiable. The evidence across the cited literature points toward a consistent theme: preventive, combined strategies are more stable than reactive, single-method interventions (Figure 2).

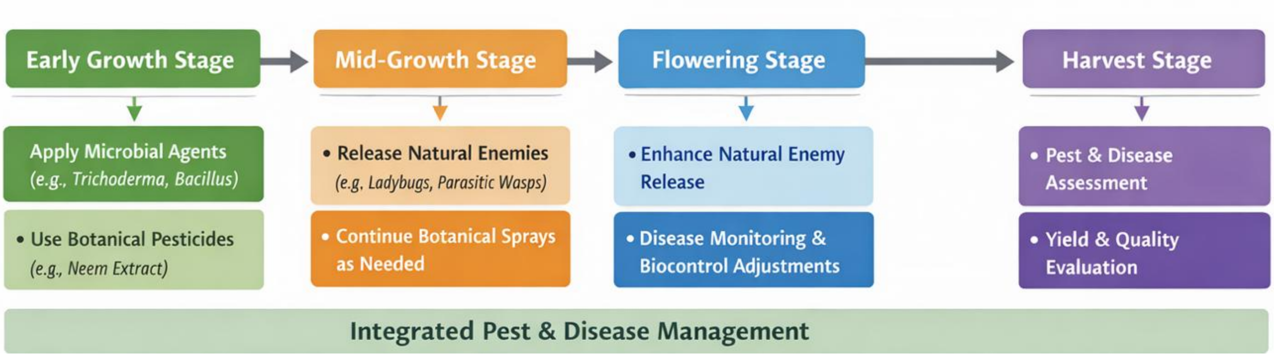

Figure 2 Integrated biological control workflow for Hangbaiju

A useful way to conceptualize this is to treat biological control as a layered system: soil health and preventive microbial inoculation reduce baseline disease pressure; selective botanicals provide flexible suppression tools for sudden pest increases; and natural enemies provide ongoing regulation, especially for pests with cryptic behavior or soil stages. This layered logic is consistent with (i) the Bacillus meta-analysis emphasizing preventive strength, (ii) the Trichoderma–bacteria synergy review emphasizing compatibility and formulation, and (iii) field/greenhouse demonstrations showing strong pest suppression when natural enemy life-history is matched to pest life-cycle vulnerabilities (Serrão et al., 2024).

4 Evaluation of Field Application Effect

4.1 Comparative effectiveness of different control measures

When comparing biological control measures, the most honest approach is to compare "effectiveness profiles" rather than pretending that each tool is measured on the same scale in the same environment. Field outcomes depend on pest species, crop stage, temperature/humidity, application timing, and sometimes the surrounding landscape.

Still, several quantitative anchors are available. In greenhouse chrysanthemum, releases of *Stratiolaelaps scimitus* achieved a reported 74.9% reduction in thrips density relative to the untreated greenhouse by late September. This level of suppression is operationally meaningful, particularly because it targets a soil stage that foliar sprays can miss.

For botanical insecticides on chrysanthemum, the 2024 evaluation under plastic house conditions reports that *Chrysanthemum cinerariaefolium* extract at 3.0–3.5 g/L achieved average efficacies of 76% and 72% against *Aphis gossypii*, and was the most consistent among tested botanicals. While *A. gossypii* is not the same as *Macrosiphoniella sanborni*, this study is still relevant for Hangbaiju because it provides a realistic magnitude of botanical suppression in chrysanthemum and supports the idea that botanicals can be more than marginal add-ons (Hutapea et al., 2024).

For microbial disease suppression, the Bacillus meta-analysis across 2000–2021 literature provides a broad benchmark: Bacillus-based biocontrol reduced disease by about 60% relative to controls, with higher efficacy in preventive contexts. This is not Hangbaiju-only, but it is a strong evidence synthesis that can guide expectations and program design (Serrão et al., 2024).

Hangbaiju-specific microbial evidence is available for Fusarium-related wilt management where Streptomyces metabolites were tested; reported results include stronger protective than therapeutic effects, reinforcing the practical principle that microbial control is best deployed before pathogen populations and vascular symptoms surge.

4.2 Effects on yield and product quality

Yield in Hangbaiju is inseparable from product quality because market grading is often driven by flower appearance, cleanliness, and consumer experience. A narrow harvest window means suboptimal timing can reduce both yield (lost harvest) and quality (flowers past peak or damaged). The Tongxiang survey described in the dataset paper emphasizes that Hangbaiju is harvested within a short period for best properties, linking agronomic timing directly to product value (Zang et al., 2023).

The aphid contamination case shows a quality dimension that is almost a “binary defect”: if aphid bodies appear in tea infusion, the product may be rejected regardless of yield. In this context, control measures that remove adults during bloom—without adding new residue concerns—can protect quality even if their effect on biomass yield is indirect. The attractant-baited yellow sticky traps described by Cao et al. are explicitly positioned as an “environmental sound measure” to combat bloom-stage aphids and reduce their presence in flowers (Cao et al., 2024). Microbial inoculants may also affect quality through plant physiology and nutrient use efficiency. The co-inoculation study in cut chrysanthemum reports improved growth and quality compared with single-strain inoculation and soil conditioner application, and connects these outcomes to changes in nutrient accumulation and gene expression in metabolic and signaling pathways. Although this was conducted in a cut-flower context rather than Hangbaiju tea production, it supports a plausible mechanism by which microbial management could improve Hangbaiju flower uniformity and stress resilience—traits that contribute to usable harvest (Wang et al., 2024).

4.3 Comparison with chemical control methods

A fair comparison with chemical control should acknowledge that chemical programs can deliver rapid suppression, especially when pest outbreaks are acute. Yet three comparative shortcomings often push Hangbaiju systems toward integrated biological control.

First, chemical sprays can be poorly matched to pest behavior. Thrips’ cryptic behavior and life cycle phases reduce spray contact efficacy, and resistance development can further erode performance. The chrysanthemum thrips biocontrol study uses this as a rationale for shifting toward biological control and IPM approaches.

Second, chemical control can undermine biological regulation by harming beneficial microbes and disrupting soil or rhizosphere functions. The PGPR study explicitly flags negative effects of chemical control on beneficial microbes, supporting the argument that the long-run “cost” of chemical programs includes ecological degradation and potentially rising disease susceptibility (Wang et al., 2024).

Third, chemical control during bloom is constrained by product identity and consumer perception. The bloom-stage aphid case provides a direct comparison: the study reports that traps combining yellow sticky boards with a complex aphid sexual attractant had a control effect "significantly superior" to spraying imidacloprid, while also offering a non-spray alternative during the sensitive bloom period. This is one of the most concrete Hangbaiju-linked comparisons accessible in the present evidence set (Cao et al., 2024).

4.4 Economic benefits and application value

Without inventing cost or profit data, the most responsible way to discuss economic benefits is to focus on mechanisms by which biological control can create value and on the accounting framework growers or cooperatives can use to evaluate interventions.

In Hangbaiju, value creation can occur through (i) preventing stand loss from soil-borne diseases, (ii) stabilizing harvestable flower quantity within the narrow harvest window, and (iii) protecting marketability via reduced contamination or defect rates (such as aphid bodies in tea infusion). The available Hangbaiju aphid study is explicitly framed around consumer experience and product contamination, implying that pest suppression can translate into better product acceptance even if biomass yield changes are not reported (Cao et al., 2024). A practical field evaluation can compute the net benefit of a biological control package as:

$$\Delta II=(Y_b\cdot P_b-C_b)-(Y_c\cdot P_c-C_c)$$

where Y is saleable yield (not just biomass), P is price (often quality-graded), and C is total control cost (inputs + labor + application time). For Hangbaiju, "saleable yield" should be adjusted for contamination defects and harvest timing losses, reflecting the narrow harvest window reported for Tongxiang (Zang et al., 2023).

From a technology-adoption standpoint, biological control has application value when it reduces operational risk. The Bacillus meta-analysis suggests that preventive applications can deliver stronger control, and the Trichoderma–bacteria synergy review emphasizes that compatibility and formulation are key for performance—both points underscore that economic benefit depends on reliable, scalable delivery rather than theoretical efficacy alone (Table 1) (Serrão et al., 2024).

5 Case Study

5.1 Background of the case

This case study is organized around Tongxiang-linked Hangbaiju production constraints and two documented control problems that directly link pest pressure to product acceptance: bloom-stage aphid contamination and soil-borne wilt risk. Tongxiang, Zhejiang is repeatedly referenced in accessible Hangbaiju literature as a major production region, and a surveyed expansion to nearly 4000 hm^2 with a narrow ≈25-day harvest window underscores why these problems are operationally disruptive (Zang et al., 2023).

The planting and management context highlighted in the accessible studies reflects typical field constraints: dense plantings that complicate scouting and treatment precision, strong dependence on short-term labor availability during harvest, and high sensitivity of marketability to defects that are visible in the brewed tea. In this setting, "management practice" is not only a set of agronomic steps but also an implicit risk strategy: preventing late-season emergencies that cannot be safely or economically solved during the harvest rush (Figure 3) (Zang et al., 2023).

Pest and disease occurrence in this case is characterized by (i) a bloom-stage aphid (*Macrosiphoniella sanborni*) that hides within flowers and can be harvested with the product, and (ii) Fusarium-associated wilt, with evidence indicating *Fusarium incarnatum* as a causal agent in chrysanthemum wilt cases, driving interest in microbial antagonists or metabolite-based control (Cao et al., 2024).

5.2 Implementation of biological control measures

The core implementation evidence here comes from two peer-reviewed studies that address different control windows but are complementary in an integrated Hangbaiju program.

Table 1 Traceable effect benchmarks from recent chrysanthemum/Hangbaiju-relevant biological control studies.
(Values are reported outcomes from cited sources; they are not newly generated data.)

Control category	Target problem	Example intervention (study context)	Reported effect indicator	Practical note for Hangbaiju adoption
Natural enemy (predatory mite)	Thrips (soil stage contribution)	*Stratiolaelaps scimitus* releases in greenhouse chrysanthemum	74.9% reduction vs. untreated greenhouse by late September	Strong where thrips pupate in soil; complements foliage management and reduces spray dependence during hot seasons (Jung et al., 2019).
Botanical insecticide	Aphids on chrysanthemum (*Aphis gossypii*)	*Chrysanthemum cinerariaefolium* extract, 3.0–3.5 g/L, plastic house	Average efficacy 76% and 72% at 3.0 and 3.5 g/L	Suggests botanicals can deliver operationally meaningful suppression, but consistency and timing are crucial (Hutapea et al., 2024).
Microbial biocontrol (meta-level)	Plant diseases (broad)	Bacillus-based BCAs across studies (2000–2021 synthesis)	~60% disease reduction vs. negative controls	Highlights preventive-strength principle; informs expectation management and program design (Serrão et al., 2024).
Microbial metabolite (Hangbaiju-focused)	Fusarium-related wilt in chrysanthemum	*Streptomyces diastatochromogenes* 1628 metabolites vs. *Fusarium incarnatum*	Protective > therapeutic effects reported in pot trials	Supports preventive use and integration with soil management; direct Hangbaiju relevance (Cao et al., 2019).
Behavioral/physical control (Hangbaiju field)	Bloom-stage aphid contamination risk (*M. sanborni*)	Yellow sticky boards baited with complex aphid sexual attractant; trap spacing 7 m × 8 m	Trapping control effect superior to imidacloprid spray (qualitative superiority claim in abstract)	Especially aligned with bloom-stage “clean product” needs; reduces need for late spraying (Cao et al., 2024).

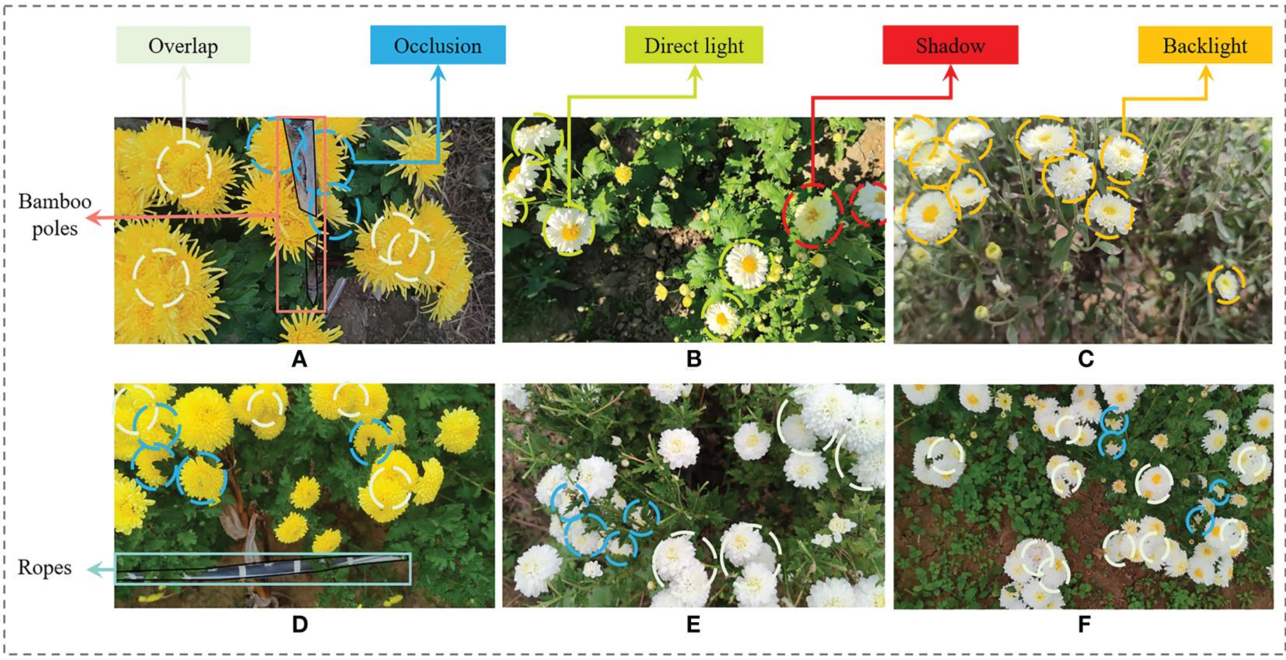

Figure 3 The category to which the sample images belong and their number in the related chrysanthemum dataset: (A) Jinsihuangju-01314, (B) Hangbaiju-00063, (C) Bo-chrysanthemum-11093, (D) Wuyuanhuangju-03285, (E) Gongju-00002, and (F) Chuju-00110 (Adopted from Zang et al., 2023)

For bloom-stage aphids, Cao et al. developed a control approach that combines olfactory and visual cues: a complex aphid sexual attractant (composed by mixing seven plant volatile components with nepetalactone at a specified volume ratio) was used to bait chrysanthemum-yellow sticky boards. Traps were deployed in Hangbaiju fields with spacing of 7 m × 8 m, and the trap bottom positioned just above plant tops (≈1 cm in the described setup) (Cao et al., 2024).

For soil-borne wilt management, the Hangbaiju Fusarium study identifies *F. incarnatum* as the pathogen and evaluates metabolites of *Streptomyces diastatochromogenes* 1628 as a biocontrol input. The study design includes in vitro inhibition endpoints and pot-trial evaluation, which is typical of microbial biocontrol development pipelines where greenhouse/pot performance is used as a bridge toward field formulation and delivery.

A practical integrated implementation, faithful to these sources, would therefore deploy microbial protection preventively (pre-plant or early growth) and rely on non-spray "clean harvest" interventions during bloom. In my experience reading the chrysanthemum biological control literature, this split design—microbes early, traps/low-residue tools late—often aligns better with on-farm logistics than trying to replace every chemical spray with a biological spray at the same timing (Serrão et al., 2024).

5.3 Analysis of control effectiveness

For the bloom-stage aphid problem, the published evidence emphasizes qualitative superiority of the trapping strategy relative to chemical spraying in the described field context. The Acta Ecologica Sinica paper reports that the chrysanthemum-yellow sticky boards baited with the complex sexual attractant caught "a large number" of aphid adults and that their control effect on the aphid population was "significantly superior" to spraying imidacloprid. The study also provides behavior-based evidence supporting mechanism: multiple volatile components at specified concentrations attracted adult aphids, and yellow color was slightly more attractive than bud green in field phototaxis trials (Cao et al., 2024). For wilt suppression, the Hangbaiju Fusarium/ Streptomyces study reports measurable protective and therapeutic effects in pot tests, with a consistent pattern that protective effects exceed therapeutic effects. This is a meaningful signal for implementation: the biological control input should be deployed before severe vascular symptoms, consistent with the broader Bacillus meta-analysis finding that preventive inoculation generally yields higher efficacy than therapeutic use across many plant disease contexts.

Comparison with conventional chemical control can be framed as follows. Aphid control: the trap-based approach outperformed imidacloprid spray in field effectiveness (as reported). Wilt management: microbial metabolites provide protective/therapeutic effects but are better framed as preventive tools than emergency cures, unlike some chemical fungicide programs. This difference is not a disadvantage; it is a design constraint that integrated programs exploit by shifting part of control earlier in the season, when intervention is easier and less risky for product quality (Cao et al., 2024).

5.4 Yield and economic benefit analysis

The accessible bloom-stage aphid study does not report yield gains in kg or yield loss avoided; it is primarily framed around control efficacy and "clean product" outcomes. For Hangbaiju, however, product acceptance is a form of economic yield. If infestation leads to aphid bodies in tea infusion and consumer rejection, then reducing adult aphids during bloom protects not only flowers but the market pathway that turns those flowers into revenue. In this sense, the economic benefit is plausibly concentrated in reduced defect rate and improved consumer acceptance, even if biomass yield is not explicitly measured (Cao et al., 2024).

For the wilt study, the phrase "huge yield loss" is used to motivate the work, but the accessible search-level summaries emphasize pathogen identification and biocontrol effect estimation rather than a complete farm-economics dataset. Without inventing numbers, the economic logic should be expressed as risk reduction: effective preventive microbial control reduces stand loss probability and stabilizes plant health, which can preserve harvestable flowers within the narrow harvest window described for Tongxiang.

A practical on-farm evaluation can combine (i) avoided spray costs during bloom due to trap deployment, (ii) reduced labor and compliance risk from late chemical applications, and (iii) avoided revenue loss from downgraded or rejected product. This can be calculated using simple farm accounting (Section 4.4), but the present review does not assign numerical values without traceable reports (Cao et al., 2024).

5.5 Case summary and practical insights

First, timing is not a minor detail; it is the structure of effectiveness. Trap-based control is matched to the bloom-stage contamination risk and can outperform a conventional spray in that stage, while microbial disease suppression is most credible as a preventive input rather than a last-minute cure.

Second, combination strategies succeed when they combine different mechanisms rather than duplicating the same mechanism. The aphid strategy combines visual and olfactory cues; microbial strategies combine antagonism and induced resistance; botanical tools combine feeding deterrence and growth disruption with relatively low impact on beneficials. Integrated programs that mix these mechanisms are less likely to fail from a single weak link (such as poor spray coverage or short persistence) (Cao et al., 2024).

Third, scalability depends on formulation and farmer-facing simplicity. The Trichoderma–bacteria synergy review explicitly notes compatibility and formulation as key steps. In Hangbaiju, where harvest labor and timing are already tight, a biological strategy that adds complex, frequent operations is unlikely to be adopted widely, even if biologically "promising" (Poveda and Eugui, 2022).

6 Existing Problems and Limitations

6.1 Instability of control effects

A recurrent critique of biological control is "instability," but much of this instability is predictable when the control tool is deployed in a way that contradicts its mode of action. The Bacillus meta-analysis shows that protective inoculation tends to outperform therapeutic application, implying that using microbial tools only after disease has surged will systematically produce disappointing results (Serrão et al., 2024).

Similarly, botanical insecticides can show variable results when pest population stage structure and plant developmental stage shift. The botanical insecticide chrysanthemum trial describes that aphid populations and their spatial distribution changed across plant developmental stages, and different botanical treatments produced different responses. This suggests that timing and concentration are not optional details but the determinants of whether botanicals behave as reliable tools (Hutapea et al., 2024).

Natural-enemy–based control can also appear unstable when environmental conditions exceed the organism's tolerance or when pesticide programs unintentionally remove the enemies. Even in the successful thrips control study, the authors note very high summer temperatures and still report effective suppression, but this is a reminder that natural enemies have climatic and ecological requirements that must be built into the management plan (Jung et al., 2019).

6.2 Influence of environmental conditions

Hangbaiju is field-grown in complex outdoor scenes where light, shade, wind, and plant overlap are significant enough that even computer vision studies treat these as major confounding factors. From a biological control perspective, the same field complexity translates into microclimate variation: humidity pockets, shading effects on leaf wetness duration, and uneven coverage for sprays or microbial applications (Zang et al., 2023). Botanical pesticides' low residual power—identified as a strength for safety and selectivity—can also be a limitation under heavy rainfall or intense sunlight, where persistence may be too short to control rapidly reproducing pests. The azadirachtin review emphasizes low residual power and also discusses practical problems of application and the need for improved stability or controlled release approaches (Kilani-Morakchi et al., 2021).

Microbial agents likewise depend on environmental fit. Survival, colonization, and antagonistic activity vary with temperature, soil moisture, organic matter, and interactions with resident microbiota. This is one reason why consortium approaches and formulations are central in current research: not because single strains are uninteresting, but because field stability often requires buffering against environmental variability (Poveda and Eugui, 2022).

6.3 Technical promotion challenges

Promoting biological control in Hangbaiju is partly a technology-transfer challenge. Many tools require (i) quality-controlled products, (ii) correct timing, and (iii) operational discipline (monitoring, threshold decisions, record keeping). These requirements can conflict with smallholder constraints or with rapid expansion of planting area where extension services cannot keep up.

The Tongxiang survey cited in the dataset paper explicitly notes labor constraints during the short harvest window, which implies that a biological control program that demands intensive late-season operations is less likely to be adopted. In other words, technical promotion requires designing programs that reduce complexity during the most labor-constrained period, not adding new chores (Zang et al., 2023).

Compatibility across measures is another promotion challenge. For example, botanicals may be "low toxicity" to natural enemies in general, but actual compatibility depends on formulation, dose, and life stage of beneficial organisms. The azadirachtin review notes that neem-based insecticides can have slight to moderate toxicity and that pre-imaginal stages may be more susceptible in laboratory conditions, implying that real-world programs must be designed with selectivity awareness rather than assuming universal safety (Kilani-Morakchi et al., 2021).

6.4 Cost and farmer awareness issues

Biological control is often perceived as costly because benefits are distributed across time: preventive microbial inoculation may prevent future losses but does not always produce immediately visible "knockdown," and conservation biological control produces diffuse benefits that are harder to attribute to a single purchase.

However, cost perception also depends on what the farmer is optimizing. In Hangbaiju, where consumer rejection from contaminants can erase value quickly, investments in bloom-stage non-spray control (like trapping) may be economically rational even if they do not increase biomass yield. The bloom-stage aphid study provides an unusually direct link between pest presence and consumer experience, which can be used in extension messaging to reframe cost-benefit discussions around product acceptance, not only yield (Cao et al., 2024).Farmer awareness is also tied to clarity of protocols. The most adoptable approaches tend to have simple rules: when to apply, how often, and what success looks like. The more biological control relies on complex, multi-step mixtures or frequent monitoring without accessible decision support, the more it risks underuse or misuse—both of which produce "instability" that is actually a training and support failure (Poveda and Eugui, 2022).

7 Optimization Strategies and Future Perspectives

7.1 Optimization of integrated control strategies

For Hangbaiju, optimization begins by matching control tools to phenological windows. Based on the narrow harvest period, the program should be designed so that heavy interventions happen before bloom and harvest, with bloom-stage emphasis on clean, non-residue measures such as trapping and selective botanicals only when necessary (Zang et al., 2023).

Microbial optimization should prioritize preventive inoculation and appropriate doses, consistent with the Bacillus meta-analysis findings. When disease suppression is the goal, protocols should explicitly define preventive timings (e.g., seedling stage, early vegetative stage, post-transplant), rather than leaving microbial products as “rescue” inputs (Serrão et al., 2024).

Where possible, multi-microbe approaches should be evaluated through the lens of compatibility and delivery. The Trichoderma–bacteria synergy review suggests that co-inoculations can exceed the sum of their parts, but it also highlights formulation challenges. For Hangbaiju, this indicates a future direction: develop locally validated consortia that can be applied through existing equipment and that tolerate local storage and transport conditions (Poveda and Eugui, 2022).

7.2 Strengthening technical guidance and training

Training programs for Hangbaiju biological control should be built around decision points that farmers already face: “When do I act?” and “What can I do during bloom without risking product quality?” The bloom-stage aphid study provides a compelling educational anchor because it translates ecological theory (olfactory + visual cues) into a concrete field practice (trap spacing, lure composition, deployment height) (Cao et al., 2024).Similarly, the thrips predatory-mite study provides a clear narrative about why chemical sprays struggle (behavior, resistance) and how biological control can exploit pest life cycle vulnerabilities (soil stage). Such case-based teaching is often more persuasive than abstract IPM slogans because it explains causality and gives farmers a mental model they can apply to new problems (Jung et al., 2019).

Extension guidance should also incorporate compatibility rules. For example, where botanicals are used, training should include selectivity and timing to protect beneficial organisms, reflecting the nuanced risk assessments described for azadirachtin and other botanicals (Kilani-Morakchi et al., 2021).

7.3 Promoting standardization and large-scale application

Standardization is crucial for scale because biological control is sensitive to product quality and operational timing. For Hangbaiju, existing standardization infrastructure is already present in production and GI frameworks. The national GI standard for Hangbaiju signals that standardization and traceability are already a market expectation, and provincial standards on production technical protocols further indicate institutional support for codifying best practices.

In the biological control domain, standardization should focus on protocol reproducibility: defined concentrations, application intervals (or monitoring triggers), and minimum quality requirements for microbial preparations or lures. The success of field trapping in the aphid study is partly due to explicit protocol details (trap color, lure composition ratio, spacing), which is a template for scalable biological control recommendations (Cao et al., 2024).For microbial products and consortia, standardization should include viability metrics, storage conditions, and application methods compatible with farmer equipment. Without this, “biological control” becomes an inconsistent category perceived as unreliable, even when the underlying biology is sound (Poveda and Eugui, 2022).

7.4 Development of sustainable and green cultivation systems

The future of Hangbaiju biological control is likely to be less about replacing one pesticide with one biopesticide and more about designing cultivation systems where pest and disease pressure is structurally reduced. This includes soil health management, crop rotation, prevention-focused microbial inoculation, ecological regulation of pests using cues and traps, and deliberate support of natural enemies.

In the chrysanthemum research landscape, future directions include microbiome management and integration of molecular tools, but the near-term “green cultivation system” for Hangbaiju can be built with already-available practice: preventive microbial inoculation strategies, selective botanicals such as azadirachtin where appropriate, and bloom-stage trapping to protect product cleanliness. The 2015–2025 chrysanthemum review explicitly frames microbiome management and integrated approaches as priorities for sustainable protection (Chen et al., 2025).

In my judgment, the strongest sustainable pathway is one that respects Hangbaiju’s product identity: it is not a crop where “cosmetic damage” is acceptable, because the flower itself is consumed. Therefore, greens systems must protect both agronomic output and consumer confidence, and biological control fits best when it is implemented as a quality-protection strategy as much as a pest-suppression strategy (Cao et al., 2024).

8 Conclusion

Biological control in Hangbaiju cultivation is not a single technology but a portfolio of tools that can be matched to the crop’s most sensitive windows—especially the narrow harvest period and the bloom-stage quality constraints of an edible flower. Evidence from chrysanthemum and Hangbaiju-relevant studies shows that microbial-based measures can provide meaningful disease suppression when used preventively, botanical pesticides can achieve operationally relevant reductions of aphid populations under protected cultivation, and natural enemies can substantially suppress pests such as thrips when their life cycles are strategically targeted.

Integrated approaches generally outperform single methods in robustness. The strongest designs are layered: preventive microbial management for soil and early-season health, selective botanicals when rapid suppression is necessary, and bloom-stage non-spray measures such as attractant-baited trapping to protect “clean product” outcomes. The key future direction is to translate these strategies into standardized, farmer-friendly protocols that fit local labor constraints and preserve consumer trust in Hangbaiju as an edible, health-associated product.

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Reference

Baldin E.L.L., Schlick-Souza E.C., Soares M.C.E., Lopes N.P., Lopes J.L.C., Bogorni P.C., and Vendramim J.D., 2020, Insecticidal and inhibitory effects of Meliaceae and Asteraceae extracts to silverleaf whitefly, Horticultura Brasileira, 38(3): 280-287.
https://doi.org/10.1590/s0102-053620200307

Cao Y., Han S., Li J., Huang G., Han B., and Wang M., 2024, Chemical and visual cues from Chrysanthemum morifolium cultivar 'Hangbaiju' plant to attract Macrosiphoniella sanborni during its blooming stage and their application against the aphid, Acta Ecologica Sinica, 44(6): 2609-2620.

Cao Z., Shentu X., and Yu X., 2019, Identification of the pathogens causing Fusarium wilt disease in Chrysanthemum morifolium Ramat and control effect of Streptomyces diastatochromogenes 1628, Chinese Journal of Biological Control, 35(2): 265-271.

Chen Y., Han L., Ye T., and Xie C., 2025, Research progress on diseases and pests of chrysanthemum (2015-2025), International Journal of Molecular Sciences, 26(19): 9767.
https://doi.org/10.3390/ijms26199767

El-Sayed I.M., and El-Ziat R.A., 2021, Utilization of environmentally friendly essential oils on enhancing the postharvest characteristics of Chrysanthemum morifolium Ramat cut flowers, Heliyon, 7: e05909.
https://doi.org/10.1016/j.heliyon.2021.e05909

Fu X., Su J., Yu K., Cai Y., Zhang F., Chen S., Fang W., Chen F., and Guan Z., 2018, Genetic variation and association mapping of aphid (Macrosiphoniella sanborni) resistance in chrysanthemum (*Chrysanthemum morifolium* Ramat), Euphytica, 214: 21.
https://doi.org/10.1007/s10681-017-2085-z

Hutapea D., Rahardjo I.B., Rachmawati F., Yulia N.D., and Budiarto K., 2024, Efficacy of some botanical insecticides against *Aphis gossypii* Glover (Hemiptera: Aphididae) on chrysanthemum, Journal of Entomological and Acarological Research, 56: 12173.
https://doi.org/10.4081/jear.2024.12173

Jung D.O., Hwang H.S., Kim S.Y., and Lee K.Y., 2019, Biological control of thrips using a self-produced predatory mite Stratiolaelaps scimitus (Acari: Laelapidae) in the greenhouse chrysanthemum, Korean Journal of Applied Entomology, 58(3): 233-238.

Kilani-Morakchi S., Morakchi-Goudjil H., and Sifi K., 2021, Azadirachtin-based insecticide: Overview, risk assessments, and future directions, Frontiers in Agronomy, 3: 676208.
https://doi.org/10.3389/fagro.2021.676208

Li J., Hu H., Mao J., Yu L., Stoopen G., Wang M., Mumm R., de Ruijter N.C.S., Dicke M., Jongsma M.A., and Wang C., 2019, Defense of pyrethrum flowers: *Repelling herbivore*s and recruiting carnivores by producing aphid alarm pheromone, New Phytologist, 223(3): 1607-1620. https://doi.org/10.1111/nph.15869

Poveda J., and Eugui D., 2022, Combined use of Trichoderma and beneficial bacteria (mainly Bacillus and Pseudomonas): Development of microbial synergistic bio-inoculants in sustainable agriculture, Biological Control, 176: 105100. https://doi.org/10.1016/j.biocontrol.2022.105100

Rahardjo I.B., Hutapea D., Marwoto B., and Budiarto K., 2021, Effects of several botanical insecticides applied in different periods to control aphids (*Macrosiphoniella sanborni*) on chrysanthemum, Agrivita Journal of Agricultural Science, 43(3): 495-506. https://doi.org/10.17503/agrivita.v43i3.2669

Rahardjo I.B., Marwoto B., and Budiarto K., 2020, Efficacy of selected plant extracts to control leafminer (*Lyriomyza* spp.) in chrysanthemum, Agrivita Journal of Agricultural Science, 42(1): 37-44. https://doi.org/10.17503/agrivita.v42i1.2219

Serrão C.P., Ortega J.C.G., Rodrigues P.C., and de Souza C.R.B., 2024, Bacillus species as tools for biocontrol of plant diseases: A meta-analysis of twenty-two years of research, 2000-2021, World Journal of Microbiology and Biotechnology, 40: 110. https://doi.org/10.1007/s11274-024-03935-x

State Administration for Market Regulation, and Standardization Administration of China, 2008, Product of geographical indication-Hangzhou white chrysanthemum (Hangbaiju), GB/T 18862-2008.

State Administration for Market Regulation, 2022, Hangbaiju production technical specification, DB33/T 2443-2022.

Wang Y., Fang X., Zhou Y., Liao Y., Zhang Z., Deng B., Guan Z., Chen S., Fang W., Chen F., and Zhao S., 2024, Transcriptome analysis of growth and quality response of chrysanthemum to co-inoculation with Bacillus velezensis and Pseudomonas aeruginosa, Scientia Horticulturae, 326: 112722. https://doi.org/10.1016/j.scienta.2023.112722

Wang Y., Zhang W., Hong C., Zhai L., Wang X., Zhou L., Song A., Jiang J., Wang L., Chen F., and Chen S., 2024, Chrysanthemum morifolium CmHRE2-like negatively regulates the resistance of chrysanthemum to the aphid (Macrosiphoniella sanborni), BMC Plant Biology, 24: 33-65. https://doi.org/10.1186/s12870-024-04758-6

Zang S., Shu L., Huang K., Guan Z., Han R., Valluru R.V., Wang X., Bao J., Zheng Y., and Chen Y., 2023, Image dataset of tea chrysanthemums in complex outdoor scenes, Frontiers in Plant Science, 14: 1134911. https://doi.org/10.3389/fpls.2023.1134911

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Factors Influencing Honey Quality in Different Production Environments

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Abstract As a natural and nutritious food product, the quality of honey is subject to the combined influence of various environmental factors. Based on a comprehensive system of quality evaluation indicators, this paper systematically analyzes the mechanisms by which different environmental conditions impact honey quality, examining aspects such as physicochemical properties, nutritional composition, and functional activity. The study focuses specifically on exploring the pathways through which climatic factors (temperature, humidity, and precipitation), geographical environments (altitude, soil type, and vegetation), and ecological settings (pollution levels and biodiversity) influence honey quality. Furthermore, by integrating an analysis of nectar source plant structure, bee population characteristics, and foraging behaviors, the paper elucidates the underlying causes behind variations in honey composition. Additionally, the study examines the impact of processing and storage conditions on the stability of honey quality, and validates the pivotal role of environmental factors in shaping honey quality through comparative case studies of representative regions. The findings indicate that environmental conditions ultimately determine the nutritional value and sensory attributes of honey by influencing the composition of nectar source plants and the foraging behaviors of bees. This paper provides a theoretical foundation and practical reference for optimizing honey production environments and enhancing product quality.

Keywords Honey quality; Environmental factors; Nectar source plants; Climatic conditions; Quality evaluation

1 Introduction

Honey is a natural sweetener valued for its nutritional, sensory and medicinal properties, and its quality strongly shapes consumer trust, market price and regulatory control (Awulachew, 2025). Quality is defined by a combination of sensory, physicochemical, microbiological and bioactive parameters, which in turn depend on botanical and geographical origin, bee species, and production and storage conditions. The rapid growth of international trade, coupled with rising demand for “natural” and premium honeys, has intensified concerns around quality deterioration and fraud, making rigorous characterization of honey quality an important scientific and economic issue (Ntakoulas et al., 2024).

From a regulatory and technical perspective, honey quality is typically evaluated through moisture content, sugar profile (fructose, glucose, sucrose, reducing sugars), electrical conductivity, free acidity, diastase activity and hydroxymethylfurfural (HMF), alongside melissopalynological and sometimes sensory analyses. These parameters are codified in international and regional standards to ensure product stability, prevent fermentation, and detect overheating or poor handling (Vîjan et al., 2023). At the same time, honey contains minerals, organic acids, phenolics, flavonoids, enzymes and volatile compounds that both influence its health value and provide fingerprints of botanical and geographical origin (Geană et al., 2020). Consequently, research has increasingly examined how soil, climate, floral resources, beekeeping practices, processing and storage jointly shape these physicochemical and bioactive traits in diverse production environments.

Current research spans broad mapping of composition and stability, as well as specialized work on authenticity and origin. Large regional surveys have quantified how floral origin, harvest year, region and climate affect sugars, acidity, conductivity, HMF and enzyme activities, often revealing significant differences among honey types and areas, and identifying non-compliant or adulterated samples (Tsagkaris et al., 2021). Comparative studies of local versus imported honeys, or honeys from contrasting climates, show consistent impacts of geographical origin and production conditions on moisture, enzyme activity, acidity, color and mineral content, with implications for both quality grading and the suitability of current standards (Vîjan et al., 2023). Parallel research has developed and applied multivariate chemometric tools and advanced analytical platforms (chromatography, spectroscopy, NMR, isotope ratios, LC-MS/MS) to classify honeys by botanical and geographical origin and to detect adulteration, complementing routine physicochemical tests (Gela et al., 2023; Ntakoulas et al., 2024; Tasić et al., 2024).

Despite this progress, several gaps remain regarding how specific production environments-defined by combinations of climate, floral landscape, management practices and post-harvest handling-jointly influence honey quality. Many studies focus on one country or region, one dimension of environment (e.g., floral or geographical origin alone), or on authenticity rather than integrated quality profiles across environments (Yayinie et al., 2021; ALaerjani and Mohammed, 2024). The present study addresses these gaps by systematically examining factors influencing honey quality in different production environments, relating standard physicochemical indicators and selected bioactive or compositional markers to environmental and management variables across multiple contexts (Tsagkaris et al., 2021; Awulachew, 2025). By integrating quality assessment with detailed information on floral sources, climatic conditions and beekeeping and processing practices, and by applying multivariate analysis to resolve patterns, this work aims to clarify how environment-specific factor combinations shape honey properties and compliance with standards (Puścion-Jakubik et al., 2020; Raweh et al., 2023; Insha et al., 2024). The study's novelty lies in its comparative, environment-oriented design and its focus on linking practical production conditions to measurable quality outcomes, thereby informing region-adapted quality control, supporting fair trade and guiding producers toward practices that maintain or enhance honey quality in diverse production systems (Vîjan et al., 2023).

2 Honey Quality Evaluation Indicator System

2.1 Physicochemical parameters

Physicochemical parameters form the backbone of legal standards for honey identity and quality. Key indices include moisture, sugar profile (fructose, glucose, sucrose), pH, free acidity, electrical conductivity, color, hydroxymethylfurfural (HMF) and diastase activity (Kivima et al., 2021). These parameters indicate freshness, proper ripening, resistance to fermentation, and heat or storage damage, and they underpin Codex and regional limits used worldwide (Pătruică et al., 2022). Large surveys show that most commercial honeys fall within these limits, but out-of-range moisture and HMF values are common signals of poor processing or storage (Ayton et al., 2025).

Physicochemical profiles are also powerful tools for authentication and differentiation of botanical and geographical origin. Studies in Romania, Portugal, Chile and elsewhere demonstrate that electrical conductivity, acidity, color, enzyme activity and basic sugars can discriminate monofloral types and confirm label claims when combined with melissopalynology and chemometric analysis (Khan et al., 2024). Stable carbon isotope ratios and protein-sugar $\delta 13C$ differences further support the detection of C4 plant syrup adulteration while still relying on the same core physicochemical dataset (Suárez-Ramos et al., 2023). Thus, physicochemical parameters simultaneously support compliance, traceability and fraud detection.

2.2 Nutritional components

Honey's nutritional value is largely determined by its carbohydrate fraction, supplemented by small but important amounts of proteins, amino acids, minerals, vitamins, organic acids and a wide range of phenolic compounds (Valverde et al., 2022). Fructose and glucose dominate energy supply, while oligosaccharides, amino acids (especially proline), minerals and organic acids contribute to metabolic and technological properties. Detailed analyses from different regions show substantial variation in mineral levels and organic acids with botanical origin, highlighting the need to consider production environment when assessing nutritional quality (Becerril-Sánchez et al., 2021; Suárez-Ramos et al., 2023).

Beyond basic nutrients, phenolic compounds and flavonoids are central to honey's functional nutrition. Numerous studies link higher total phenolics and flavonoids to stronger antioxidant capacity and often to darker color, making these components key indicators of nutritional "added value" (Sharma et al., 2023). Recent reviews conclude that phenolic acids and flavonoids, rather than vitamins, account for most of the in-vitro antioxidant activity, and they are increasingly used as markers of both botanical origin and health potential (Sharma et al., 2023). Newer work extends this to enriched products, showing that additions such as bee pollen or plant ingredients can modify phenolic profiles and thus enhance or modulate nutritional and functional attributes (Habryka et al., 2021).

2.3 Sensory quality and functional activity

Sensory quality-color, aroma, flavor, mouthfeel and overall acceptability-is a decisive factor for consumer choice and price. Descriptive sensory studies from Estonia, Italy and Malaysia show that floral, fruity, berry-like, sour and sweet attributes, together with color intensity, vary systematically with botanical origin, bee species and climatic conditions (Qi et al., 2025). Standardized sensory panels and flavor wheels enable objective profiling, while chemometric integration with physicochemical data reveals strong correlations between sensory traits and parameters such as color, acidity, conductivity and moisture (Ayton et al., 2025). These tools allow sensory quality to be treated as a measurable indicator, not only a subjective impression.

Functional activities-especially antioxidant and antimicrobial effects-are now widely included in honey quality evaluation systems. Studies across many floral types report that honeys richer in phenolics and flavonoids exhibit stronger radical-scavenging and reducing power, as well as higher in-vitro antimicrobial activity against foodborne and clinical pathogens (Becerril-Sánchez et al., 2021). Reviews consolidating recent work confirm robust positive relationships between phenolic/flavonoid content and antioxidant assays, while emphasizing that botanical origin and production environment modulate these links (Molina et al., 2020; Sharma et al., 2023). Advanced assessments combining artificial "electronic senses" with bioactivity tests further demonstrate that sensory fingerprints, composition and antimicrobial performance are tightly interconnected, reinforcing the view that functional activity indicators are integral to modern honey quality assessment (Machado et al., 2022; Qi et al., 2025).

3 Mechanisms of Environmental Impact on Honey Quality

3.1 Climatic factor

Climatic conditions during nectar flow and harvest determine key physicochemical parameters such as moisture, acidity, enzyme activity and HMF, thereby influencing stability and compliance with standards (Pham et al., 2022). Higher ambient humidity and rainfall around the apiary, or harvesting during rainy periods, increase moisture content and water activity, favoring fermentation and shortening shelf life (Mărgăoan et al., 2024). Seasonal patterns of temperature and precipitation modify flowering phenology and nectar concentration, which in turn alter sugar profiles and antioxidant capacity across seasons, even when bee species and management remain constant (Şireli and Saylak, 2025). At the same time, hot climates accelerate non-enzymatic browning and degradation of thermosensitive compounds in stored honey, raising HMF and sometimes lowering diastase, so that honeys from hot or desert regions may exceed conventional HMF limits despite correct beekeeping practices (Homrani et al., 2020; Shakoori et al., 2023).

Post-harvest exposure to elevated temperature and ambient humidity continues these climatic effects through storage and processing (Glevitzky et al., 2025). Studies in different climatic zones show that honeys stored or produced under hot tropical or desert conditions tend to accumulate more HMF and may show reduced enzyme activities compared with those from cooler or temperate areas, even when initial composition is comparable (Shakoori et al., 2023). Regression analyses further demonstrate that honey moisture is significantly driven by environmental relative humidity, confirming that macro- and micro-climatic water balance directly constrains safe moisture ranges (Pham et al., 2022; Mărgăoan et al., 2024). Consequently, climatic factors operate through both field-level (nectar concentration, flowering, bee foraging) and post-harvest (heating, storage) pathways to shape honey quality trajectories over time (Homrani et al., 2020; Harbane et al., 2024).

3.2 Geographic environment

Geographic setting controls altitude, soil characteristics and vegetation patterns, which together define the floral resources available to bees and thus the baseline chemical profile of honey (Petrova et al., 2024). Differences among regions in soil composition and climate generate distinctive mineral fingerprints and variations in sugars, conductivity, acidity and HMF, allowing discrimination of honeys from contrasting landscapes within the same country. In multi-regional datasets, altitude and regional climate interact with floral composition to produce significant variability in fructose, glucose, sucrose, electrical conductivity and acidity, while some parameters such as moisture remain relatively stable across sites (Shakoori et al., 2023; González et al., 2024). Altitudinal gradients also influence phenolic content and antioxidant capacity, with honeys from higher elevations frequently showing increased phenolic levels compared with lowland counterparts of similar botanical origin (Mărgăoan et al., 2024; Ayton et al., 2025).

Vegetation distribution driven by geography determines the mix of nectar and honeydew sources, which has strong effects on phenolic profiles, antioxidant activity and color. Comparative studies across bioclimatic zones show that Mediterranean and forest-type vegetation, or honeydew-rich environments, yield darker honeys with higher phenolics, flavonoids and antioxidant capacity than honeys from more open or agricultural areas (Mračević et al., 2020; ALaerjani and Mohammed, 2024). Spatial contrasts between arid, sub-humid and humid regions are reflected in clear groupings of samples by physicochemical and antioxidant traits, underlining the joint influence of regional flora and environmental conditions. Thus, geographic environment acts primarily through its control of soil-climate-vegetation mosaics, shaping both the inorganic and organic fraction of honey and providing geographical signatures that can be exploited for authentication and quality differentiation (González et al., 2024; Inaudi et al., 2025).

3.3 Ecological Environment

The broader ecological environment—including contamination resulting from heavy metals, pesticides, and industrial activities—alters the composition of honey and may compromise its safety, while simultaneously enabling it to serve as a bioindicator (Inaudi et al., 2025). Even when basic physicochemical parameters remain within acceptable limits, honey sourced from areas impacted by mining or intensive agriculture typically exhibits higher concentrations of metals—such as lead, cadmium, iron, copper, and zinc—compared to honey from protected areas (Vîjan et al., 2023). In these contaminated environments, elevated metal levels coincide with reduced concentrations of phenolic and flavonoid compounds, as well as diminished antimicrobial activity, indicating that pollution is accompanied by a decline in functional quality attributes. Consequently, chemical fingerprinting based on inorganic elements can aid in assessing the bioactivity of honey. This approach plays a pivotal role in tracing geographical origins while simultaneously reflecting the status of environmental pollution, thereby closely linking honey quality control with ecosystem monitoring (Inaudi et al., 2025).

Biodiversity and landscape quality also shape the characteristics of honey by enriching the sources of pollen and nectar and by buffering the effects of environmental stressors (Petrova et al., 2024). Regions characterized by rich and heterogeneous vegetation provide a wide array of pollen types and diverse nectar chemistries; this manifests in the honey as a complex profile of phenolic compounds, alongside robust antioxidant and antimicrobial activities (ALaerjani and Mohammed, 2024). Conversely, simplified or degraded ecosystems—including highly urbanized areas or regions under intensive cultivation—may limit plant diversity and expose honeybees to higher pollutant loads, thereby narrowing the spectrum of phytochemicals found in the honey and potentially increasing the risk of residue levels exceeding regulatory limits (Raweh et al., 2023). By integrating botanical data, physicochemical properties, and pollutant data, a series of recent studies has highlighted the dual role played by honey: it serves both as a product whose quality is contingent upon ecological integrity, and as a sensitive indicator for monitoring environmental health across diverse production settings (Inaudi et al., 2025).

4 Influence of Botanical Origin and Nectar Source Structure

4.1 Differences between monofloral and multifloral honey sources

Monofloral honeys are characterized by the predominance of pollen and nectar from a single plant, confirmed by melissopalynology and supported by distinctive physicochemical and volatile profiles. Reviews of monofloral honeys (e.g., acacia, chestnut, lavender, thyme, sunflower) show that each type tends to present specific patterns of volatile organic compounds that generate characteristic aroma fingerprints, even when produced in different countries (Machado et al., 2020; Hussein and Seid, 2024). Studies on Portuguese and Italian monofloral honeys further demonstrate that parameters such as electrical conductivity, color, sugar spectrum, diastase activity, and specific VOCs allow discrimination among floral types, underscoring the tight link between single dominant nectar sources and honey composition (Ballarin et al., 2022).

Multifloral honeys, in contrast, result from bees collecting nectar from many species simultaneously, reflecting high floral richness and flexible foraging strategies. Pollen analyses in Ethiopia and other regions reveal that a substantial proportion of harvested honeys are multifloral or bifloral, often containing dozens of pollen types and integrating contributions from herbs, shrubs, and trees across habitats (Tesfu and Habte, 2021; Bratosin et al., 2025). Diet studies using pollen traps and landscape analysis show that, even where mass-flowering crops dominate nectar intake, a wide diversity of wild and weed species contributes to pollen and, to a lesser extent, nectar, particularly between major crop flowering peaks (Inaudi et al., 2025). Consequently, multifloral honeys often show more complex but less predictable profiles, and their quality depends strongly on the composition and continuity of surrounding floral communities (Machado et al., 2022).

4.2 Impact of plant species on honey composition

Individual plant species imprint specific chemical signatures on honey through their nectar and secondary metabolites. Comparative analyses of honeys from sunflower, linden, rapeseed, acacia, and other floral types show that botanical origin significantly affects moisture, sugars, electrical conductivity, free acidity, phenolics, flavonoids, and antioxidant activity. For example, sunflower honey has been reported with particularly high conductivity and phenolic and flavonoid contents, while multifloral honeys in the same region exhibit higher total sugars, illustrating how plant traits translate into distinct nutritional and technological properties (Machado et al., 2022). Similarly, monofloral honeys from thyme, linden, and buckwheat often contain markedly higher total phenolics and antioxidant capacities than acacia honeys, reflecting species-specific phenolic profiles (Jaśkiewicz et al., 2025).

Beyond bulk parameters, plant species influence detailed phenolic and volatile fingerprints that support authentication and origin differentiation. Studies on varietal honeys show that particular phenolic acids and flavonoids (e.g., caffeic, p-coumaric acids, quercetin, hesperetin, chrysin) reach characteristic levels in honeys from thyme, coriander, jujube or other specific plants, enabling chemometric models to classify monofloral types with high accuracy (Akbari et al., 2020). Reviews of honey volatiles identify dominant aroma compounds associated with citrus, chestnut, eucalyptus, lavender, rosemary, and other sources, while also highlighting that interactions with geography and processing can complicate marker selection (Machado et al., 2020; Hussein and Seid, 2024). Overall, the plant species providing nectar act as primary drivers of compositional diversity, setting the baseline upon which environmental and management factors further operate.

4.3 Analysis of flowering cycles and nectar source stability

Flowering phenology and seasonal continuity of nectar sources critically influence both the botanical origin of honeys and the stability of their quality. Whole-farm and landscape-scale studies reveal strong seasonal fluctuations in nectar production, with clear peaks and “gaps” when floral resources are scarce relative to pollinator demand (Vîjan et al., 2023). In temperate farmlands, two main nectar peaks often occur around mass-flowering crops, separated by a late-spring dearth (“June gap”), and further periods of low availability in early spring and late summer-autumn (Figure 1) (Inaudi et al., 2025). These temporal mismatches affect which plant species dominate nectar flows at different times, creating seasons where monofloral honeys (e.g., rapeseed, sunflower) are likely, and intervening periods when bees rely more on diverse weeds, hedgerows, and semi-natural habitats, favoring multifloral profiles (Inaudi et al., 2025).

At regional scales, characterization of honeybee floras and flowering seasons shows that specific months can be classified as major nectar flow and honey flow periods linked to key plant species, while other months act as dearth or minor harvest seasons with different dominant flora (Silva et al., 2025). For instance, highland and lowland areas may produce monofloral honeys from distinct species in separate peak seasons, with additional minor harvests from other taxa in between (Tesfu and Habte, 2021). Longitudinal studies of pollen diversity also indicate that bees collect pollen from relatively few species in early spring and late summer, but from many more taxa in mid-season, and that semi-natural habitats become especially important for maintaining pollen diversity at the end of the flowering season (Vîjan et al., 2023). Consequently, the timing and stability of nectar sources-defined by flowering cycles, habitat composition, and landscape management-play a central role in determining whether honeys are monofloral or multifloral and how consistent their botanical and quality attributes are across years and production environments.

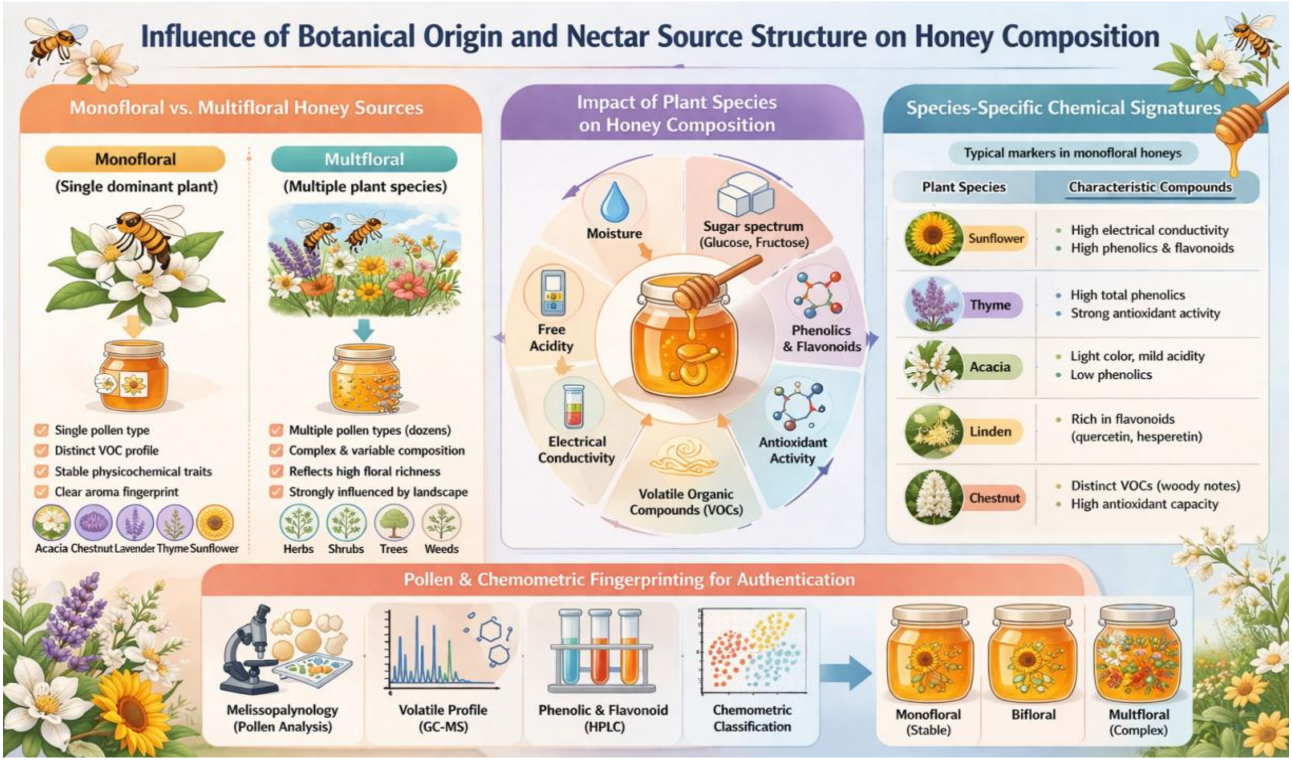

Figure 1 Influence of botanical origin and nectar source structure on honey composition and quality

5 Factors Related to Bee Populations and Foraging Behavior

5.1 Impact of bee breed differences on honey quality

Differences among bee species and breeds can modify the physicochemical and bioactive characteristics of honey by shaping which flowers are visited, how nectar is processed, and how honey is stored. Comparative work on Apis mellifera and stingless bees shows that bee type significantly affects moisture, free acidity, HMF, phenolic content, and antioxidant capacity of honey, with stingless bee honeys generally having higher moisture, higher acidity, and different phenolic profiles than A. mellifera honeys (Dupont et al., 2025). These interspecific differences are linked not only to floral choices but also to morphological and behavioral traits, such as body size, flight range, and preferred plant strata, which together define access to nectar sources and conditions of in-hive ripening (Dwarka et al., 2025).

A systematic meta-analysis further indicates that bee type (A. mellifera vs. various stingless genera) is a significant covariate explaining variability in phenolics, flavonoids, and several physicochemical parameters across countries and floral sources (Dwarka et al., 2025). Stingless bees often forage on smaller flowers and perform shorter flights than A. mellifera, and they store honey in cerumen pots rather than wax combs, introducing additional material and microenvironmental effects that can alter the final honey composition. These findings imply that breed or species composition of bee populations is a primary biological factor underlying regional patterns in honey quality, even under comparable environmental conditions (Dupont et al., 2025).

5.2 Foraging behavior and nectar collection efficiency

Foraging behavior determines which nectar and pollen resources are incorporated into honey, thereby influencing sugar profiles, micronutrients, and specialized metabolites. DNA metabarcoding and palynological studies show that honey bees use only a fraction of available flowering plants and display marked selectivity for both nectar and pollen, with plant choices shifting strongly over time and among colonies in the same landscape (Zaldívar-Ortega et al., 2024). Colonies typically exploit a high number of potential floral resources, yet at any moment most of the collected nectar or pollen is dominated by a few taxa, indicating dynamic but non-random preferences that structure honey's botanical fingerprint and metabolite composition (Zaldívar-Ortega et al., 2024).

At the colony level, resource allocation between nectar and pollen foraging is plastic and responds to internal nutritional status and external resource profitability. Experimental manipulations demonstrate that the profitability of nectar sources (sugar concentration or flow rate) alters the probability that bees switch between nectar and pollen collection and changes the colony-level ratio of pollen to non-pollen foragers. Other behavioral studies reveal that only a minority of highly active foragers perform a disproportionate share of trips, and that foraging performance improves with experience, indicating that colony nectar intake and honey yield are strongly dependent on the activity and learning of this subset of workers (McMinn-Sauder et al., 2022). These behavioral mechanisms link environmental floral heterogeneity and colony state to the efficiency and selectivity of nectar collection, shaping both honey quantity and quality.

5.3 Hive health status and microbial influences

Hive health status influences honey quality through both nutritional dynamics and microbiological processes within the colony. Comparative analysis of healthy and stressed hives shows that honey from healthy colonies has significantly higher phenolic content, antioxidant capacity, and antimicrobial activity than honey from stressed hives, despite similar floral resources. Stressed colonies, characterized by poor brood patterns, low bee populations, or disease signs, produce honey with reduced "activity," suggesting that suboptimal colony condition can depress the enrichment of phenolics and other bioactive constituents during nectar processing and storage (Layek et al., 2020).

Microbial communities in and around the hive also modulate nectar transformation and honey properties. Work on nectar-associated yeasts demonstrates that colonization by Metschnikowia reukaufii alters nectar amino acid levels, sugar composition, and volatile emissions, but honey bees avoid yeast-inoculated nectar even when pollen is present, indicating that microbial metabolites can deter foraging and thereby indirectly influence which nectars enter the hive (Yokota et al., 2024). Parallel profiling of gut, hive, and honey microbiomes in healthy versus stressed colonies reveals significant differences in core and opportunistic taxa, with stressed hives showing higher microbial diversity that may reduce the capacity to exclude pathogens and potentially affect honey stability and antimicrobial characteristics (Layek et al., 2020). Together, these results highlight that hive health and associated microbial communities constitute an important internal environmental layer governing honey quality in addition to external floral and climatic factors.

6 Impact of Processing and Storage Conditions

6.1 Honey harvesting and initial processing methods

Harvesting and early handling steps such as extraction, filtration, and moisture reduction shape the initial "starting point" for subsequent quality evolution. Studies on acacia and rape honeys show that centrifugation and filtration generally reduce concentrations of enzymes, phenolics, minerals, and other constituents (due to removal or dilution of pollen and suspended solids), while moisture reduction at elevated temperatures increases HMF and can lower diastase activity (Mohammad et al., 2023; Gruznov et al., 2024). Even relatively mild preheating (45 °C-55 °C) and vacuum drying steps significantly decreased diastase and phenolic contents in rape honey, indicating that functional components are sensitive to routine industrial treatments (Scepankova et al., 2024).

At the same time, some processing innovations seek to minimize quality loss compared with conventional pasteurization. High-pressure processing (HPP) has been evaluated as an alternative that improves microbial safety with less impact on HMF, diastase, and antioxidant activity during storage than standard heat pasteurization (Kamboj et al., 2024). In a comparative study, pasteurization at 78 °C/6 min immediately eliminated microorganisms but led to HMF and diastase values outside legal limits after 12-24 months, whereas HPP-treated and raw honeys stored for 24 months remained within standards and retained higher antioxidant capacity. These findings highlight the need to balance microbiological safety with the preservation of freshness markers and bioactive compounds when selecting initial processing methods.

6.2 Heat treatment and changes in enzyme activity

Heat treatment is widely used to reduce viscosity, dissolve crystals, and lower moisture content, but it directly drives HMF formation and enzyme inactivation. Kinetic studies demonstrate that temperatures above about 60 °C cause a sharp increase in HMF and a concomitant decline in diastase, with both effects accelerating as time and temperature rise. Heating at 40 °C for long periods had little effect on HMF or diastase, whereas exposure at 60 °C-100 °C caused regular HMF increases and diastase decreases, implying relatively narrow thermal windows for safe processing. Similar patterns were observed in Apis florea honey, where treatments at 55 °C-65 °C for several hours raised HMF by up to ~45% and reduced diastase and invertase activities by ~60%-72%, clearly demonstrating enzyme deactivation at higher temperatures and longer durations (Wu et al., 2022).

Thermal processing also affects antioxidant-related compounds and activities. Experiments at 63 °C for up to 30 min on different floral honeys showed increases in HMF and reductions in total phenolic content, accompanied by declines in DPPH radical-scavenging and FRAP values in some honeys (Jaya et al., 2022). A broader review concludes that thermal treatment significantly influences honey color, moisture, HMF, diastase, microbial load, and antioxidant parameters, and that time-temperature combinations must be carefully managed to moderate these negative effects (Bhure et al., 2025). Overall, evidence indicates that maintaining temperatures at or below about 40 °C-45 °C during routine handling, and limiting exposure at 60 °C-65 °C to very short times, is critical to preserve enzyme activity and bioactive components while achieving technological goals (Al-Rubaie, 2022).

6.3 Impact of storage environment (temperature, light, duration) on quality

Storage temperature and duration are major drivers of long-term changes in freshness markers and sensory/nutritional quality. Multiple studies show that room-temperature or warm storage increases HMF and reduces diastase, whereas cool storage markedly slows these reactions (Ramly et al., 2021). For example, sunflower honey stored 18 months at ~22 °C in the dark exhibited a 17-fold increase in HMF and a two-fold decrease in diastase, though moisture and free acidity remained relatively stable. Two-year storage of varietal honeys at room temperature caused about a 79% rise in HMF and ~67% reduction in diastase, whereas storage at 4 °C or below limited HMF increases to ~25%-33% and produced smaller enzyme losses, also reducing color changes (Kędzierska-Matysek et al., 2025).

A systematic review of 43 studies confirms that prolonged storage can deteriorate sensory, nutritional, and antioxidant properties and promote fermentation, granulation, and quality indicators such as increased HMF and decreased diastase and invertase (Manickavasagam et al., 2024). Work on stingless bee and other honeys further indicates that storage at 40 °C accelerates HMF formation and loss of phenolics and antioxidants, while storage at 4 °C-5 °C preserves bioactive compounds and antimicrobial activity much better (Rababah et al., 2024).

7 Case Study: Comparative Analysis of Honey Quality Under Different Regional Environmental Conditions

7.1 Selection of study areas and sample collection methods

Comparative evaluation of regional environmental effects on honey quality requires sampling areas that differ clearly in climate, land use, pollution history, and topography. Recent work has contrasted honeys from multiple Romanian regions with distinct geological and anthropogenic backgrounds, using 61 samples from eight areas to capture gradients in soil composition, industrial activity, and atmospheric inputs (Shakoori et al., 2023). Other studies designed regional comparisons by selecting contrasting agroecological zones or climatic regions (e.g., cold vs. hot climates, or temperate vs. tropical zones), ensuring that differences in humidity, temperature, vegetation and land use were adequately represented for subsequent chemometric analysis (Rosiak et al., 2021).

Sampling strategies typically combine spatial replication with careful control of production variables to isolate environmental effects. Multifloral honeys are often collected directly from beekeepers or apiaries to avoid market adulteration and to link samples reliably to specific landscapes and pollution sources (Rosiak et al., 2021).

In-depth regional surveys record for each sample the geographic coordinates, altitude, surrounding land use, and potential anthropogenic influences (industrial plants, waste sites, intensive agriculture), together with harvest year and extraction methods, creating metadata needed to interpret elemental and quality differences (Bora et al., 2024). Such designs allow later use of multivariate statistics to relate honey quality patterns to mapped environmental drivers.

7.2 Comparison of honey quality indicators under different environmental conditions

Regional comparisons usually start from a core set of physicochemical indicators (moisture, pH, sugars, electrical conductivity) and extend to mineral profiles, potentially toxic elements and antioxidant traits. Multi-regional studies in Romania and Serbia have shown that contents of K, Mg, Na and microelements (Al, Cu, Fe, Mn, Ni, Zn, Se) vary significantly with both geographical and botanical origin, while toxic metals such as Pb and Cd may exceed safety limits in some polluted areas (Bora et al., 2024). Parallel assessment of pH, moisture, color and antioxidant activity across agroecological zones or climatic regions reveals systematic regional differences, with some zones producing darker honeys with higher phenolic and flavonoid contents and stronger antioxidant capacity (Smith et al., 2021).

In landscapes with known industrial or agro-industrial pollution, honey quality comparisons focus more explicitly on food safety and bioindicator functions. Surveys in historically contaminated Romanian regions found Pb and Cd concentrations consistently above international safety thresholds, with spatial analysis showing higher contamination at sites closer to former industrial facilities and along suspected atmospheric transport pathways (Shakoori et al., 2023). Other long-term or broad-scale datasets using honey as a recorder of environmental lead demonstrate that metal concentrations and Pb isotopic compositions differ between urban, rural, and agricultural settings, reflecting both local emissions and larger-scale legacy pollution (Awolu et al., 2025). Together, these comparative indicators reveal how divergent environmental conditions translate into distinct nutritional profiles, contaminant burdens and functional qualities of honey (Figure 2).

Figure 2 Comparative analysis of honey quality under different regional environmental conditions

Hangzhou Linan Hongjian Bee Breeding Family Farm utilizes the superior natural environment and high-quality honey crops in the area to produce high-quality honey with a good taste, which is highly welcomed by consumers (Figure 3).

Figure 3 Natural Environment and Honey Source Crops of the Base of Hangzhou Linan Hongjian Bee Breeding Family Farm (Left: Environment; Middle: Honey Harvesting; Right: Honey Source Crop Loquat) (Photo by Hongjian Chen)

7.3 Analysis of results and identification of key environmental influencing factors

Multivariate statistics are central to disentangling which environmental factors most strongly shape regional honey quality. Principal component analysis and clustering applied to large elemental datasets have successfully discriminated honeys by geographical origin, with the first two principal components often explaining most of the variance and separating samples into groups that correspond to specific regions or pollution histories (Bora et al., 2024). In such analyses, high loadings for elements like K, Mg, Mn, Cu or Pb highlight combined influences of soil geochemistry, agricultural practices and industrial emissions, while dendrograms based on metal profiles frequently align with known regional boundaries or land-use types (Shakoori et al., 2023).

Case studies from polluted agro-industrial landscapes further illustrate how altitude, distance to emission sources and land-use pattern emerge as key predictors of contaminant levels in honey. Spatial analyses linking Pb, Cd, Cu and Zn concentrations to former industrial facilities show clear gradients, with higher burdens near emission hotspots and evidence for atmospheric transport effects at elevated sites (Shakoori et al., 2023). Comparative work across urban centers and agricultural islands using Pb isotopes indicates that sampling resolution (city vs. regional vs. global) determines whether local infrastructure, agricultural operations or the legacy of leaded gasoline dominates the signal recorded in honey (Awolu et al., 2025). By integrating these chemometric and spatial findings, regional case studies identify a small set of critical environmental drivers-geology and soil, industrial and traffic emissions, climate and altitude-that must be considered when interpreting honey quality differences and designing targeted monitoring and regulatory measures.

8 Conclusion and Outlook

Current research converges on the view that honey quality emerges from the interaction of environment, colony management, and processing, rather than any single factor. Reviews emphasize that climate, floral and geographical origin, pollution, hive health, and processing/storage jointly determine physicochemical traits, contaminant loads, and functional properties such as antioxidant and antimicrobial activity. Environmental degradation, intensive agriculture, and improper storage or adulteration add new pressures, but the same studies show that honey and other bee products are sensitive bioindicators, linking product quality directly to ecosystem status and human practices.

Management and technology are equally central. Syntheses of best beekeeping practices demonstrate that hive management, Varroa control strategies, and biosecurity programs are key drivers of colony survival, productivity, and the production of residue-safe, high-quality honey. Parallel reviews of analytical methods highlight rapid advances in authenticity and quality assessment, including NIR spectroscopy, chemometrics, and metabolomics, which can classify floral and geographical origin and detect adulteration or contamination with increasing precision. Together, these findings show that both good environmental stewardship and evidence-based technical tools are needed to secure honey purity and excellence.

Improving honey quality requires systematic reduction of environmental stressors around apiaries. Reviews on pollution and contaminants recommend limiting pesticide and antibiotic use, enforcing maximum residue limits, and monitoring heavy metals, PAHs, and other xenobiotics that can accumulate in honey and compromise safety. Because bees and honey effectively mirror local contamination, integrating honey-based biomonitoring into regional environmental surveillance can both protect pollinators and provide early warning of risks to food quality.

At landscape scale, strengthening floral resources and habitat quality is crucial. Reviews of beekeeping constraints and “good apiculture practices” emphasize preventing deforestation of nectar plants, diversifying forage, and aligning farming systems with ecologically sound practices to sustain strong colonies and high-value honeys. Urban and anthropized-area studies further suggest that thoughtful urban greening, reduced air pollution, and control of microplastics and other emerging contaminants will be increasingly important where urban honey production grows. Coordinated policies that couple habitat conservation with pollutant reduction therefore represent a primary environmental lever for improving honey quality.

Several research frontiers are emerging around measurement, contamination, and management optimization. Methodological reviews point to rapid development of NIR spectroscopy, electronic tongues/noses, metabolomics, and DNA-based tools as fast, non-destructive approaches for quality grading, authenticity, and origin tracing, with likely expansion into portable, in-field devices. Parallel work on authenticity stresses the need for integrated workflows that combine advanced extraction, hyphenated chromatography-mass spectrometry, and chemometric models to detect increasingly sophisticated adulteration and to support robust regulatory supervision.

On the stressor side, new syntheses underline rising concerns about contaminant “cocktails” and novel pollutants such as microplastics, calling for multi-residue analytical methods and updated legislation that reflect real exposure patterns in honey and bees. Beekeeping-management research is moving toward quantitative indices and scenario-based frameworks that link specific practice packages to colony health and product quality at regional scales, supporting evidence-based extension and policy. Future work integrating environmental monitoring, advanced analytics, and standardized management metrics will be essential to protect pollinators while ensuring high-quality, traceable honey in increasingly complex production environments.

References

Akbari E., Baigbabaei A., and Shahidi M., 2020, Determination of the floral origin of honey based on its phenolic profile and physicochemical properties coupled with chemometrics, International Journal of Food Properties, 23: 506-519.
https://doi.org/10.1080/10942912.2020.1740249

AlAerjani W., and Mohammed M., 2024, Impact of floral and geographical origins on honey quality parameters in Saudi Arabian regions, Scientific Reports, 14: Article 59359.
https://doi.org/10.1038/s41598-024-59359-y

Al-Rubaie W., 2022, The influence of storage conditions and heating on diastase, invertase activity and hydroxymethylfurfural in Iraqi honey, Muthanna Journal for Agricultural Sciences, 9(2): 32.
https://doi.org/10.52113/mjas04/9.2/32

Awolu O., Ikumawoyi S., Aluko B., Lawal O., and Fagbemi T., 2025, Impact of geographical variations on the physicochemical properties, antioxidant activities and viscosity of honey from Nigeria, IPS Journal of Nutrition and Food Science, 4(1): 70.
https://doi.org/10.54117/ijnfs.v4i1.70

Awulachew M., 2025, Re-evaluating honey quality: key factors influencing its purity and excellence, Food and Drug Safety, 2(1): 315.
https://doi.org/10.55121/fds.v2i1.315

Ayton J., Groves L., and Berry J., 2025, Chemical composition and quality assessment of Apis mellifera honey in Australia, Food Science and Nutrition, 13: 70160.
https://doi.org/10.1002/fsn3.70160

Ballarin C., Hachuy-Filho L., Doria M., Giffu M., Polizello D., Oliveira P., Lacerda-Barbosa P., and Amorim F., 2022, Intra-seasonal and daily variations in nectar availability affect bee assemblage in a monodominant afforested Brazilian Cerrado, Austral Ecology, 47: 21
https://doi.org/10.1111/aec.13218

Becerril-Sánchez A., Quintero-Salazar B., Dublán-García O., and Escalona-Buendía H., 2021, Phenolic compounds in honey and their relationship with antioxidant activity, botanical origin, and color, Antioxidants, 10: 11700.
https://doi.org/10.3390/antiox10111700

Bhure R., Alam M., Nanda V., Pawar V., and Saxena S., 2025, Exploring the impact of thermal processing on the quality attributes of honey: a comprehensive review, Journal of Food Process Engineering, 2: 70033.
https://doi.org/10.1111/jfpe.70033

Bora F., Andrecan A., Călugăr A., Bunea C., Popescu M., Petrescu-Mag I., and Bunea A., 2024, Comprehensive elemental profiling of Romanian honey: exploring regional variance, honey types, and analyzed metals, Foods, 13(8): 1253.
https://doi.org/10.3390/foods13081253

Bratosin E., Tit D., Purza A., Pasca M., Bungau G., Marin R., Radu A., and Gîtea D., 2025, Exploratory analysis of phenolic profiles and antioxidant capacity in Romanian monofloral honeys, Antioxidants, 14(10): 1248.
https://doi.org/10.3390/antiox14101248

Dupont Y., Balsby T., Greve M., Marcussen L., and Kryger P., 2025, Spatio-temporal variation in pollen collected by honey bees in rural-urban landscapes, PLOS ONE, 20: e0309190.
https://doi.org/10.1371/journal.pone.0309190

Geană E., Ciucure C., Costinel D., and Ionete R., 2020, Evaluation of honey in terms of quality and authenticity based on physicochemical pattern and δ13C signature, Food Control, 109: 106919.
https://doi.org/10.1016/j.foodcont.2019.106919

Gela A., Gebresilassie A., Atikem A., Damto T., and Wolde-Hawariat Y., 2023, Physicochemical properties and botanical sources of honey from Ethiopia, Journal of Food Quality, 2023: 9051595.
https://doi.org/10.1155/2023/9051595

Glevitzky M., Corcheş M., Popa M., and Vică M., 2025, Honey as a bioindicator: pollution's effects on its quality, Applied Sciences, 15(13): 7297.
https://doi.org/10.3390/app15137297

González A., De La Cruz Martínez W., Ramírez D., Martínez K., Mancera B., Puerto R., and Del Ángel Piña O., 2024, Changes in physicochemical and antioxidant properties over one year, Agro Productividad, 17(11): 2950.

Gruznov D., Gruznova O., Sokhlikov A., and Lobanov A., 2024, Effect of low-temperature storage on honey composition and antimicrobial activity, Food Processing: Techniques and Technology, 2024(2): 2512.
https://doi.org/10.21603/2074-9414-2024-2-2512

Habryka C., Socha R., and Juszczak L., 2021, Effect of bee pollen addition on polyphenol content and antioxidant activity of honey, Antioxidants, 10: 508.
https://doi.org/10.3390/antiox10050810

Harbane S., Escuredo O., Saker Y., Ghorab A., Nakib R., Rodríguez-Flores M., Ouelhadj A., and Seijo M., 2024, Contribution of botanical origin to physicochemical and antioxidant properties of Algerian honeys, Foods, 13(4): 573.
https://doi.org/10.3390/foods13040573

Homrani M., Escuredo O., Rodríguez-Flores M., Fatiha D., Mohammed B., Homrani A., and Seijo M., 2020, Botanical origin and physicochemical properties of Algerian honey, Foods, 9(7): 938.
https://doi.org/10.3390/foods9070938

Hussein O., and Seid A., 2024, Botanical origins of honeys from pollen analysis in Ethiopia, Heliyon, 10: e40101.
https://doi.org/10.1016/j.heliyon.2024.e40101

Inaudi P., Garzino M., Abollino O., Malandrino M., and Giacomino A., 2025, Honey inorganic composition as marker for botanical and geological assignment, Molecules, 30(7): 1466.
https://doi.org/10.3390/molecules30071466

Insha R., Islam M., Gomasta J., Hasan M., Amin M., Sarmin N., and Rahman M., 2024, Honey authentication in Bangladesh based on physicochemical profiling, Heliyon, 10: e40203.
https://doi.org/10.1016/j.heliyon.2024.e40203

Jaśkiewicz K., Szczęsna T., and Jachuła J., 2025, Phenolic profile and antioxidant activity dependence on botanical origin, Molecules, 30(2): 360.
https://doi.org/10.3390/molecules30020360

Jaya F., Radiati L., Estiasih T., Rosyidi D., Lastriyanto A., Junus M., et al., 2022, Honey moisture reduction using thermal methods and quality effects, E3S Web of Conferences, 335: 00026.
https://doi.org/10.1051/e3sconf/202233500026

Kamboj R., Sandhu R., and Nanda V., 2024, Effect of heating and pH on HMF and enzyme activity of honey, Food Chemistry Advances, 2024: 100766.
https://doi.org/10.1016/j.focha.2024.100766

Kędzierska-Matysek M., Teter A., Daszkiewicz T., Topyła B., Skałecki P., Domaradzki P., and Florek M., 2025, Effect of storage temperature on honey quality parameters, Agriculture, 15(6): 652.
https://doi.org/10.3390/agriculture15060652

Khan K., Malik K., Ahmad M., Naveed M., Raja I., Nazish M., et al., 2024, Nutritional composition and quality parameters of natural honey, Scientific Reports, 14: 79672.
https://doi.org/10.1038/s41598-024-79672-w

Kivima E., Tanilas K., Martverk K., Rosenvald S., Timberg L., and Laos K., 2021, Composition and antioxidant activity of Estonian honeys, Foods, 10(3): 511.
https://doi.org/10.3390/foods10030511

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Feeding Strategies for Improving Growth Performance in Goats

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Abstract Improving goat growth performance is a key objective in modern livestock production, directly influencing economic efficiency and product quality. This study systematically explores feeding strategies that enhance growth performance in goats by integrating nutritional management, feeding practices, genetic improvement, health control, and environmental regulation. The research analyzes critical growth indicators such as weight gain, feed conversion efficiency, and immune status, and evaluates the effects of optimized diet formulation, including balanced roughage-to-concentrate ratios and functional feed additives. In addition, different feeding systems and management approaches are compared to identify optimal practices. The role of genetic selection and marker-assisted breeding in improving growth traits is also discussed. A case study is presented to demonstrate the practical application and effectiveness of these strategies under farm conditions. The findings provide a comprehensive framework for improving goat production efficiency and offer valuable insights for sustainable and scientific goat farming.
Keywords Goat growth performance; Feeding strategies; Nutritional management; Feed efficiency; Genetic improvement

1 Introduction

Feeding management is a central lever for improving productivity and profitability in modern goat production systems. Goats contribute substantially to food security and rural livelihoods by supplying meat, milk, and high-value by-products in both intensive and smallholder settings, particularly in tropical and subtropical regions where they are often better adapted than larger ruminants to heat, poor-quality forages, and feed scarcity (Teixeira et al., 2024). However, suboptimal nutrition and poorly designed feeding programs remain major constraints to realizing the genetic growth potential of goats, leading to low average daily gains, delayed market age, and reduced reproductive efficiency. Recent work in replacement breeder goats has shown that relatively modest adjustments in diet composition and quantity—such as increasing total daily feed allowance and rebalancing roughage–concentrate ratios—can substantially enhance body weight gain, body condition score, and overall growth performance under smallholder conditions (Ghani et al., 2017). At the same time, climate change and rising temperatures are intensifying heat stress, altering nutrient requirements and increasing maintenance costs for thermoregulation, which makes context-specific feeding strategies even more critical for sustaining growth in hot environments. Against this background, evidence-based feeding strategies tailored to production goals, production systems, and environmental constraints are essential for improving growth performance in goats.

Goat growth performance is shaped by a wide array of interacting nutritional, managerial, and environmental factors. At the most fundamental level, growth depends on meeting energy and protein requirements that vary with genotype, physiological state, body weight, and ambient temperature. Under- or over-feeding energy markedly alters average daily gain, carcass yield, and the allometric development of muscle and internal organs in growing dairy goats, with restricted feeding decreasing growth rate, carcass meat yield, and visceral development in a weight-stage-dependent manner (Huang et al., 2024). Beyond total nutrient supply, the feeding system and diet structure strongly influence performance. Comparative assessments of stall feeding, pasture grazing, and grazing plus supplementation in small ruminants show that finishing kids and lambs solely on pasture typically reduces average daily gain and carcass yield, whereas supplemented grazing or intensive stall-feeding can match or exceed growth and carcass traits of confined systems when rations are appropriately balanced. Within intensive systems, diet form and ingredient selection are important: pelleted or hydroponic-fodder-based rations can increase intake, nutrient digestibility, and weight gain compared with conventional roughage-based diets, while manipulated starch degradability and non-forage fiber sources can improve feed efficiency and lean tissue deposition by enhancing post-ruminal starch digestion and nutrient utilization. Feed additives and specific supplements, including live yeast (*Saccharomyces cerevisiae*), mulberry leaves, and fermented roughages, have been shown to stimulate average daily gain and feed efficiency by modulating rumen fermentation, antioxidant capacity, immune status, and gut microbiota, particularly under thermal stress. In young goats, early-life feeding strategies that support rumen development—through appropriate liquid feeding, concentrate and roughage management, and functional additives—have lasting benefits on growth and health after weaning (Abdelsattar et al., 2025). Collectively, these findings highlight that growth performance in goats depends not only on nutrient level but also on feeding frequency, physical form of the diet, forage combinations, and the inclusion of targeted functional ingredients.

Building on this growing body of evidence, the present study on "Feeding Strategies for Improving Growth Performance in Goats" aims to systematically evaluate and integrate practical dietary interventions that can be implemented in commercial and smallholder contexts. The specific objectives are to: (i) summarize and compare the effects of different feeding systems (extensive grazing, semi-intensive, and intensive stall-feeding) and ration structures on growth rate, feed efficiency, and carcass-related traits in goats; (ii) assess how key ration design variables—such as energy and protein density, forage–concentrate ratio, starch degradability, forage species combinations, and physical form of the diet—modulate nutrient intake, rumen function, and growth outcomes; (iii) review and, where possible, quantify the contribution of selected nutritional strategies and feed additives (e.g., yeast, hydroponic fodder, functional forages, and plant-based supplements) to improving growth performance under heat stress and other challenging conditions; and (iv) identify feeding strategies that are both biologically effective and economically feasible across diverse production environments, with particular attention to hot climates and resource-limited systems. By integrating controlled trials, meta-analyses, and recent updates on nutrient requirements, the study seeks to provide a framework for designing context-appropriate feeding programs that enhance average daily gain, shorten finishing time, and improve overall productivity in goat enterprises. Ultimately, this work is intended to support producers, nutritionists, and policymakers in adopting feeding strategies that align improved growth performance with sustainability and resilience in goat production systems.

2 Evaluation System of Goat Growth Performance

A comprehensive evaluation system for goat growth performance integrates productive, nutritional, and health–immune indicators to assess feeding strategies effectively. Key productive traits, such as body weight and average daily gain, reflect growth capacity, while nutritional efficiency indicators like feed conversion ratio and digestibility measure how well feed is utilized. Health and immune parameters, including antioxidant status and blood indices, ensure that growth improvements do not compromise animal welfare. This integrated framework enables comparison of feeding systems, diet composition, and management practices, while also providing mechanistic insights through metabolic and rumen-related measurements, supporting the optimization of sustainable goat production.

2.1 Growth rate and body weight gain indicators

Growth rate and body weight gain are primary outcomes for evaluating feeding strategies in goats, because they integrate nutrient intake, metabolic status, and environmental conditions over time. On-farm evaluations and experimental trials typically record live weight at standardized ages (e.g. birth, 3, 6, 9, and 12 months) and compute period-specific ADG to describe growth trajectories and identify sensitive phases. For example, Arsi-Bale kids reached mean weights of 2.0, 7.6, 13.0 and 19.3 kg at birth, 3, 6 and 12 months, respectively, with corresponding daily gains between 40 and 125 g depending on age, agroecology and sex (Guyo et al., 2023). Crossbred Boer × Central Highland goats showed birth to yearling weights from 2.52 to 20.5 kg, with phase-specific gains of 31–80 g/day that were strongly influenced by Boer blood level, birth type and season (Tesema et al., 2021). Such data provide a baseline against which nutritional interventions can be judged.

Controlled feeding trials use ADG and final body weight to quantify the response to diet formulation, feeding level, feed form or supplementation. Raising Saanen dairy kids at 40, 70 or 100% of ad libitum intake produced a linear decline in ADG as feed level decreased, accompanied by lower shrunk and empty body weights, hot carcass weight and tissue yields at slaughter (Huang et al., 2024). Under thermal stress, Boer goats given fermented Pennisetum giganteum feed achieved higher ADG (48.2 g vs. lower in controls) and carcass weight while consuming less feed, illustrating how diet quality can counter environmental constraints on growth. Similar improvements in final weight and ADG have been reported when diets were supplemented with garlic skin, cecropin, or optimized concentrate levels, confirming that body weight gain indicators are sensitive tools for discriminating among feeding strategies.

2.2 Feed conversion efficiency and nutrient utilization

Feed conversion efficiency expresses how effectively goats transform feed into live weight and is central to evaluating and comparing feeding strategies economically and environmentally. FCR or feed-to-gain ratios are usually calculated as total feed intake per unit of weight gain over a defined period, while related indices such as Kleiber ratios (growth rate relative to metabolic weight) capture efficiency across growth stages. Meta-analysis of *Saccharomyces cerevisiae* supplementation in growing goats showed that yeast preparations increased ADG while having smaller overall effects on dry matter intake and FCR, indicating potential efficiency gains from altered rumen fermentation and health status (Ogbuewu and Mbajiorgu, 2023). In intensive systems, concentrate feeding frequency changed daily feed intake and ADG in Sirohi kids, but did not markedly alter FCR, suggesting that higher intake and gain can occur without proportional improvements in conversion.

Nutrient utilization is evaluated by measuring intake and apparent digestibility of dry matter and key nutrients, as well as rumen fermentation characteristics. Young Kacang goats fed diets with increasing energy density (TDN 70.0%-73.3%) showed higher intakes of organic matter, crude protein and metabolizable energy and achieved better ADG and feed efficiency at the highest energy level, even though dry matter intake and most digestibilities remained high and similar across treatments (Tahuk et al., 2024). Under heat stress, goats receiving fermented Pennisetum feed had reduced average daily feed intake yet improved F:G ratio, accompanied by enhanced antioxidant and immune status, suggesting more efficient nutrient use under challenging conditions (Figure 1) (Qiu et al., 2023). Functional additives such as garlic skin or cecropin have been linked to higher volatile fatty acid production and favorable shifts in acetate-to-propionate ratios, which support more efficient energy capture from fiber and starch, reinforcing the value of combining FCR with nutrient and rumen measurements when assessing feeding interventions.

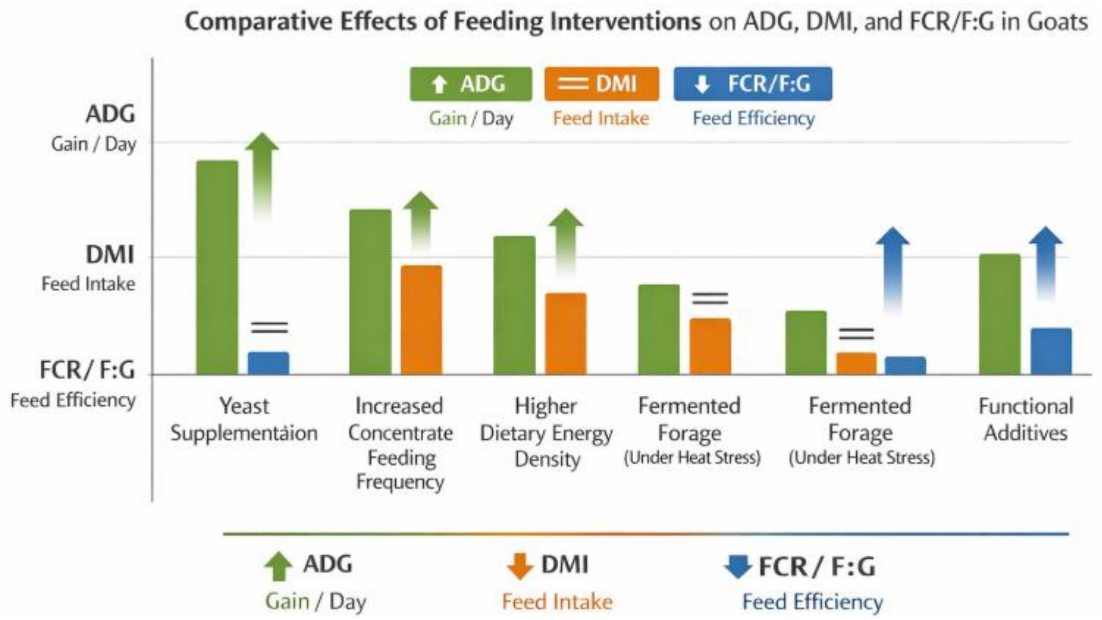

Figure 1 Comparative effects of feeding interventions on average daily gain, dry matter intake, and feed conversion efficiency in goats. The figure summarizes the relative responses of goats to yeast supplementation, concentrate feeding frequency, dietary energy density, fermented forage, and selected functional additives (Adopted from Qiu et al., 2023)

2.3 Health status and immune performance indicators

Health and immune indicators are essential components of goat growth evaluation systems, because rapid gains achieved at the expense of resilience can undermine long-term productivity. Hematological variables such as hemoglobin, packed cell volume, and leukocyte counts, together with rectal temperature and clinical observations, provide a basic assessment of health across management systems. In Beetal kids compared under stall-fed and free-range grazing conditions, stall-fed animals displayed better overall growth and health profiles, while free-range kids often showed higher antioxidant enzyme activities, reflecting differing oxidative challenges and adaptive responses (Bhinder et al., 2024). Comparisons of free-range, semi-intensive and fully barn-kept Thai native goats revealed that continuous confinement led to weight loss, elevated red and white blood cell counts, increased neutrophil-to-lymphocyte ratio, cortisol, and higher gastrointestinal parasite egg counts, highlighting how management and associated feeding patterns can induce physiological stress despite controlled nutrition (So-In, 2023).

At a finer level, immune and oxidative stress biomarkers are widely used in feeding trials to link diet composition to health-related performance. Supplementing goat diets with garlic skin enhanced serum activities of superoxide dismutase, glutathione peroxidase and catalase, reduced malondialdehyde, and elevated IgA and IgG, alongside increased anti-inflammatory cytokines (IL-4, IL-10) and reduced pro-inflammatory cytokines (IL-1β, IL-6, TNF-α) (Zhou and Shen, 2025). Cecropin supplementation similarly increased antioxidant enzyme activities, improved immunoglobulin levels, and shifted rumen fermentation and microbiota composition, coinciding with better growth and lower feed-to-gain ratio. Meta-analytic evidence for yeast additives also points to higher blood glucose, white blood cell counts and ruminal propionate and total VFA, indicating combined metabolic and immune modulation (Ogbuewu and Mbajiorgu, 2023). Together, these findings support incorporating antioxidant status, immunoglobulins, cytokine profiles and selected hematological traits into growth performance evaluation, ensuring that feeding strategies promote both productivity and robust immune function.

3 Nutritional Requirements and Diet Formulation for Goats

Nutritional requirements of goats vary with age, physiological stage, and environmental conditions, making precise feeding management essential for optimal growth. During rapid growth, energy and protein demands increase significantly, requiring adjustments in nutrient density and intake. Higher energy and protein levels generally promote better weight gain and feed efficiency, while environmental stress, such as heat, can shift nutrient use toward maintenance rather than growth. Modern feeding standards emphasize stage-specific nutrient supply, considering body weight and growth status. Mineral needs, particularly calcium and phosphorus, rise moderately with body weight, allowing for more accurate and efficient diet formulation in growing goats.

3.1 Nutritional characteristics at different growth stages

Nutritional priorities shift markedly from pre-weaning to post-weaning, finishing, and pregnancy, and feeding strategies must track these changes. Early-life goats transition from liquid to solid feeds while the rumen is still developing, so diets must support both tissue growth and rumen maturation. Energy and protein restriction in weaned kids has been shown to impair antioxidant capacity of gastrointestinal tissues, underscoring the sensitivity of this stage to nutritional insults (Abdelsattar et al., 2025). Later, during the main growth period (roughly 4-8 months), goats respond strongly to dietary energy and protein density: increasing ME concentration and CP level enhances average daily gain up to an optimum, beyond which performance may plateau or decline (Lu and Potchoiba, 1990).

Physiological state also modifies nutritional characteristics and efficiency of nutrient use. In hot environments, goats show altered requirements for sodium, potassium and phosphorus relative to widely used feeding systems, likely reflecting adaptive mechanisms to cope with heat stress and associated water and electrolyte challenges (Teixeira et al., 2024). During pregnancy, energy and protein requirements for the conceptus rise, but recent work indicates that the efficiency of ME utilization for pregnancy actually increases as gestation advances, even though absolute mineral accretion requirements grow with fetal size. Under-nutrition at critical gestational windows can compromise offspring gastrointestinal development: feed restriction in early gestation reduced small-intestinal mass, length, and villus height:crypt depth ratio in newborn kids, suggesting long-term consequences for nutrient absorption and growth potential (Figure 2) (Santos et al., 2023).

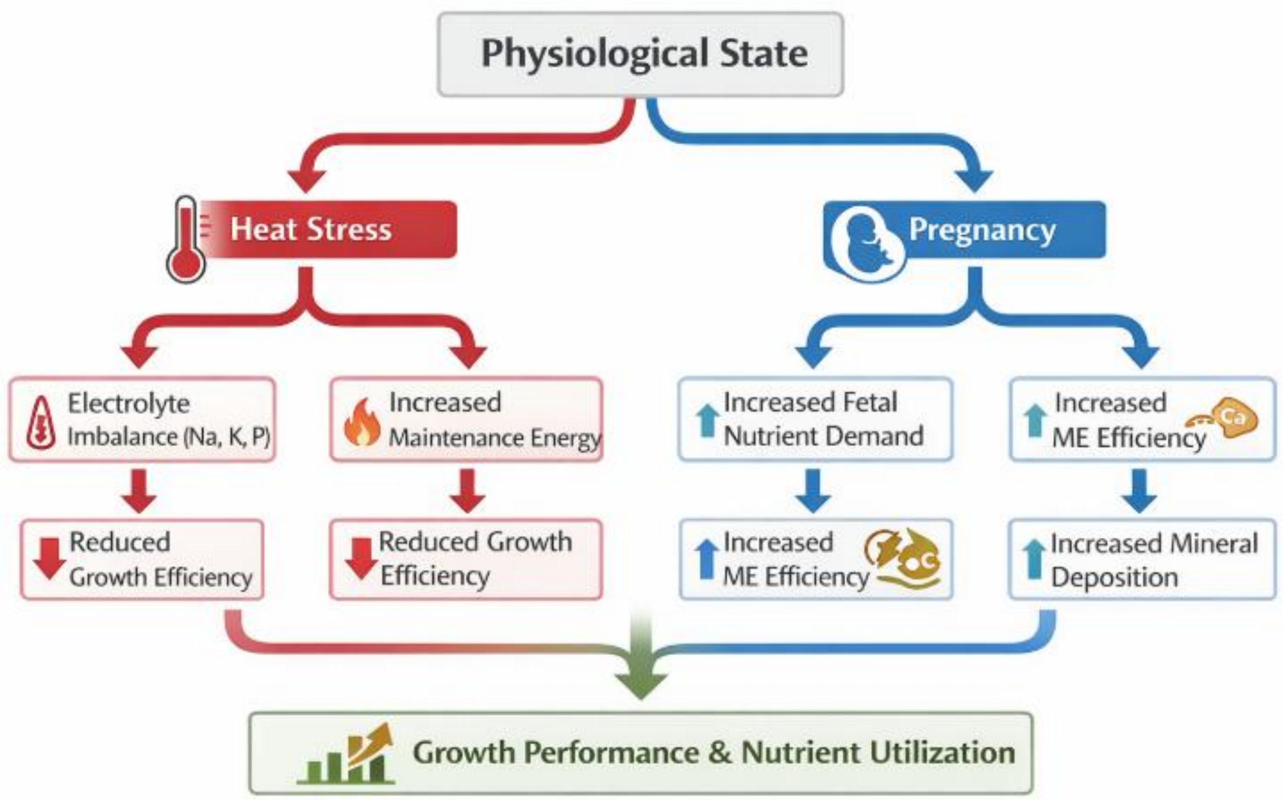

Figure 2 Effects of maternal undernutrition on gastrointestinal development in offspring goats. The diagram compares intestinal morphology under normal and restricted nutritional conditions, highlighting differences in intestinal size and villus structure (Adopted from Santos et al. 2023)

3.2 Scientific ratio of roughage and concentrate feed

Balancing roughage and concentrate is fundamental to maintaining rumen health while supplying adequate energy and protein for growth. Concentrate supplementation consistently improves dry matter intake, nutrient digestibility and growth when goats are otherwise dependent on low-quality forages or grazing alone. In Jamunapari does under semi-intensive conditions, increasing concentrate from 150 to 300 g/day alongside roughage significantly improved intake of digestible crude protein and total digestible nutrients, as well as digestibility of dry matter and crude protein (Shoshe et al., 2021). Similarly, in Barbari kids fed pulse-straw diets, raising concentrate mix to 2.1% of body weight enhanced weight gain, total VFA production and nitrogen retention, indicating more efficient nutrient utilization in finisher goats (Dutta et al., 2025).

However, excessively high concentrate and low forage can compromise rumen function, welfare, and long-term health. Rumen development in young kids benefits from higher roughage proportions: in early-weaned Balady kids, a 70:30 concentrate:roughage diet increased total volatile fatty acids, ammonia nitrogen and ciliate protozoa counts and was recommended as a high-roughage strategy for rumen development (Aziz et al., 2018). Forage-to-concentrate (F:C) ratio also affects behavior and stress; in goat kids, a 20:80 F:C diet produced superior growth but was associated with more stereotypic behaviors such as bar and bucket biting, while higher-forage diets elevated cortisol at extreme roughage levels, indicating the need to avoid both forage deficiency and excess under intensive systems (Tölü, 2025). Under comparable feeding regimes, altering concentrate:roughage ratios (3:7 vs. 5:5) changes fiber digestibility and rumen fermentation patterns, highlighting that optimal F:C ratios must be tailored to growth stage and production goals while maintaining rumen pH and microbial stability (Lin et al., 2023).

3.3 Application of functional additives

Functional additives, particularly probiotics and enzyme preparations, have emerged as effective tools to enhance growth performance and rumen efficiency in goats, especially in high-concentrate or stressful conditions. Supplementation with Bacillus subtilis and B. licheniformis, alone or combined with multi-enzyme complexes, has repeatedly improved average daily gain and final body weight in fattening goats relative to unsupplemented controls (Lu et al., 2025). These combinations can increase average daily feed intake and growth rate simultaneously, resulting in higher slaughter weights without adverse effects on serum biochemical or antioxidant indices (Lu et al., 2021). In weaned goats, complexes of Candida utilis, Bacillus coagulans, Lactobacillus acidophilus and multi-enzymes significantly increased end weight and ADG, while tending to improve digestibility of dry matter and crude fat, suggesting better exploitation of both fiber and non-fiber nutrients (Lu et al., 2022).

Beyond growth, functional additives modulate rumen fermentation, epithelial integrity, and immune status. Probiotic–enzyme combinations elevate total volatile fatty acids or specific branched-chain VFAs, improve rumen papilla morphology, and enrich fiber-degrading taxa such as Prevotellaceae and Fibrobacteres, thereby supporting more efficient fermentation of high-concentrate diets. In goats fed high-concentrate rations, probiotic supplementation increased concentrations of acetate, propionate, butyrate and total VFAs, while upregulating tight-junction proteins and anti-inflammatory cytokines (e.g., IL-10) and downregulating pro-inflammatory mediators, ultimately enhancing rumen barrier function and growth performance. Under heat stress, supplementation with *Saccharomyces cerevisiae* and Clostridium butyricum improved rumen pH, cellulolytic enzyme activities, volatile fatty acid concentrations, dry matter intake and ADG, indicating a protective effect on rumen function and productivity in challenging environments (Cai et al., 2021). Together, these findings support the targeted use of probiotics and enzymes as part of scientific diet formulation to improve growth, health and resilience in modern goat production systems (Barsila et al., 2025).

4 Optimization of Feeding and Management Practices

4.1 Comparison of intensive and grazing-combined systems

Intensive stall-feeding generally supports higher growth rates than continuous grazing, primarily through better control of nutrient supply and reduced energy expenditure on walking and thermoregulation. In Black Bengal does, daily live weight gain was significantly higher under stall feeding than under tethering, restricted grazing, or full-day grazing, even though all groups received the same level of concentrate supplementation (Moniruzzaman et al., 2002). Similar patterns were observed in Kanni Adu and Osmanabadi goats, where stall-fed or high-supplement groups achieved the greatest average daily gain and body size, while goats maintained on sole grazing showed markedly poorer performance (Jeyakumar, 2020; Da et al., 2021). These results indicate that intensive systems are particularly advantageous where high-quality forages or concentrates can be reliably supplied.

However, integrating grazing with strategic supplementation often narrows the performance gap with intensive systems while exploiting low-cost pasture resources. Reviews of small ruminant feeding systems show that kids and lambs grazing with concentrate supplementation can reach average daily gains and carcass yields comparable to or higher than those of stall-fed animals, especially when pastures are of good quality (Huang et al., 2023; Ke et al., 2023). Time-limited or restricted grazing with concentrate has also been proposed as a finishing strategy that maintains growth performance while reducing feed costs and improving some meat quality traits relative to purely indoor systems. In practical goat production, semi-intensive or grazing-combined systems thus represent a compromise, trading some control over intake for lower feed costs, more natural behavior, and potential product quality advantages.

4.2 Optimization of feeding regimes and frequency

Beyond system type, growth performance in goats is strongly influenced by the level of concentrate supplementation within a given diet. In intensively raised Barbari kids, increasing concentrate mix from 0.7% to 2.1% of body weight improved daily weight gain, dry matter intake, digestible crude protein, and total digestible nutrients, along with more favorable rumen fermentation and blood profiles (Dutta et al., 2025). Similar benefits of higher-quality or better-balanced forage-concentrate combinations were reported when guinea grass was mixed with protein-rich Indigofera, which produced the highest crude protein intake, total weight gain, and average daily gain among several forage legume mixtures. These findings support the principle that growth optimization requires both adequate energy density and sufficient rumen-degradable and bypass protein in the ration.

Feeding frequency is another key management lever for improving growth in goats. In Sirohi kids, offering a fixed amount of concentrate three times daily significantly increased total daily feed intake and average daily gain relative to once- or twice-daily feeding, with little effect on feed conversion ratio, suggesting improved utilization of nutrients rather than increased efficiency per se. Studies in Beetal kids and in goats receiving turmeric-supplemented diets likewise showed that more frequent or daily provision of the ration enhanced dry matter intake, weight gain, and body measurements compared with less frequent feeding schedules (Ahmad et al., 2014; Omotoso, 2022). Collectively, this evidence indicates that dividing the daily ration into multiple meals better matches the high metabolic rate and limited rumen capacity of young goats, stabilizing rumen conditions and supporting faster growth.

4.3 Water management and environmental control

Water availability and quality interact strongly with feed intake to determine growth performance in goats. Experiments with Nguni does showed that moderate water restriction (around 70%-80% of ad libitum) can temporarily coincide with peak dry matter intake and average daily gain, but more severe or prolonged restriction reduces gain and worsens gain-to-feed ratio, especially when combined with saline drinking water (Mpendulo et al., 2017). In related work, increasing the period of water deprivation from 0 to 48 hours led to higher compensatory water and feed intake after rehydration but significantly decreased average daily gain, final body weight, and body condition score, and increased parasite burden, underscoring the cumulative negative impact of hydric stress on productivity and health (Mpendulo et al., 2020). These results emphasize that any short-term adaptation to reduced water supply is quickly offset by losses in growth and condition when restriction is extended.

Environmental conditions, particularly heat and humidity, further modify water needs and growth responses. Under hot-humid tropical conditions, providing drinking water with pH as low as 3.8 did not adversely affect nutrient intake, water balance, or growth, and in some cases was associated with higher metabolizable energy use and daily gain compared with mildly acid water, suggesting considerable tolerance to naturally acidic sources where microbial safety is adequate (Ali et al., 2022). In tropical and semi-arid settings, higher temperature-humidity indices drive increased water intake, highlighting the importance of continuous access to clean water to maintain thermoregulation and feed intake (Mpendulo et al., 2017). From a systems perspective, integrating robust water supply, shade, and ventilation into intensive housing, and ensuring accessible watering points and microclimate refuges in grazing systems, is essential to protect growth performance as climate variability and heat stress intensify (Mugoti et al., 2025).

5 Genetic Factors and Breeding Improvement Strategies

5.1 Selection of superior breeds and utilization of hybrid vigor

Breed choice is a foundational decision for improving growth performance, because heritability estimates for body weights and average daily gain are generally moderate, allowing sustained response to selection in meat-type goats (Ofori and Hagan, 2020; Tesema et al., 2020). Crossbreeding indigenous does with specialized meat breeds such as Boer has been widely used to combine adaptation with superior growth, as shown in Boer × Central Highland goats where F_1 progeny raised semi-intensively achieved substantial gains from birth to yearling age under moderate inputs (Tesema et al., 2021). Within indigenous populations such as West African Dwarf goats, relatively high heritability for birth and weaning weights indicates that systematic selection among local animals can also deliver progress when crossbreeding options are limited.

Exploiting heterosis (hybrid vigor) can accelerate improvement, but the level of exotic blood must be carefully managed under low-input systems. In Boer × Central Highland goats, F_2 and F_3 generations did not outperform F_1 for growth and efficiency traits, and increasing Boer inheritance beyond 50% was considered uneconomical under minimal inputs, suggesting that much of the advantage lies in the first cross. Similar patterns have been reported for other crossbreeding schemes, where positive heterosis for birth and yearling weight and post-weaning growth was greatest in the initial crossbred generation before diminishing in later backcrosses (Prastowo et al., 2019; Chavala et al., 2023). These results support breeding strategies that prioritize robust F_1 or other limited-generation crosses, combined with improved nutrition and health, rather than indiscriminately increasing the proportion of specialized meat breeds.

5.2 Application of marker-assisted selection (MAS)

Marker-assisted selection (MAS) uses DNA markers associated with growth traits to enrich breeding populations for favorable alleles earlier and more accurately than phenotype-based selection alone. Genome-wide association studies (GWAS) in diverse goat populations have identified numerous single nucleotide polymorphisms (SNPs) linked to body weight, body length, height, chest circumference, and carcass traits, pointing to genes involved in skeletal growth, muscle development, and energy metabolism (Shangguan et al., 2024). In meat and dual-purpose goats, MAS for such loci can complement conventional selection indices built on estimated breeding values for weights and gains, allowing breeders to identify superior kids before full performance records are available (Moaeen-Ud-Din et al., 2022; Ncube et al., 2025).

Selection signature and candidate-gene studies provide further targets for MAS by revealing genomic regions under strong artificial or natural selection for growth. Whole-genome scans in indigenous and improved breeds have pinpointed genes related to body size, muscle accretion, and fat metabolism, including loci with functional variants such as an insertion–deletion polymorphism in PNLIPRP1 associated with enhanced early growth. Copy-number-variation and SNP-based GWAS in cashmere and meat goats have also highlighted growth-related genes involved in cell proliferation, differentiation, and key signaling pathways, suggesting that multi-marker panels could be assembled for routine MAS in breeding nuclei (Liu et al., 2025; Zhang et al., 2025). For smallholder systems, incorporating a limited set of well-validated markers into low-density genotyping tools offers a practical route to integrate genomics into growth-oriented selection programs.

5.3 Mechanisms of genetic improvement on growth performance

Genetic improvement of growth performance operates through both additive and non-additive effects on traits such as birth, weaning, and yearling weight, as well as average daily gain. Heritability estimates for these traits in crossbred and indigenous goats are typically low to moderate, implying that selection can steadily improve early growth and marketing weights when pedigree and performance records are available. Meta-analyses across small ruminants also indicate that efficiency and resilience traits have exploitable genetic variation, supporting selection for animals that maintain growth under variable environments without excessive increases in mature size or health problems (Mucha et al., 2022).

At the molecular level, growth is regulated by complex networks involving endocrine axes, structural proteins, and signaling pathways that govern muscle hypertrophy, bone growth, and nutrient use. Candidate-gene and genomic studies in goats highlight polymorphisms in growth hormone, insulin-like growth factor-1, myostatin, and multiple loci uncovered by GWAS that affect muscle growth, fat deposition, and carcass composition, thereby influencing overall growth efficiency (Shangguan et al., 2024; Ncube et al., 2025). Pathway analyses repeatedly implicate metabolic and MAPK signaling routes, along with genes affecting body size and lipid metabolism, indicating that selection on these genomic regions alters the balance between lean tissue accretion, maintenance requirements, and feed conversion (Guo et al., 2018; Zhang et al., 2025). Integrating this knowledge into breeding schemes—through indices that weigh growth, efficiency, and health, supported by genomic prediction—provides a mechanistic basis for designing goat populations with faster, more efficient growth adapted to specific feeding systems.

6 Health Management and Disease Prevention Measures

6.1 Effects of common diseases on growth performance

Infectious and parasitic diseases are major constraints on growth performance in goats, primarily by depressing feed intake, diverting nutrients to the immune response, and directly damaging target organs. Gastrointestinal nematodes (GIN) are among the most important, reducing live weight gain, carcass quality, milk yield, and reproductive performance, with particularly severe losses in resource-poor systems where control measures are limited (Rajesh et al., 2017). Meta-analysis indicates that increasing fecal egg counts in infected goats is associated with pronounced declines in average daily gain, dry matter intake, and packed cell volume, reflecting both undernutrition and anemia that undermine growth efficiency (Cei et al., 2018). Internal parasites also lower serum protein and albumin and induce oxidative stress, consistent with chronic malabsorption and inflammation that further compromise productive potential (Sarkar et al., 2024).

High burdens of GIN and other parasites are common in tropical and subtropical regions, where prevalence in goats often exceeds 80%-90% and mixed infections are the rule rather than the exception (Sontigun et al., 2025). On farms in the tropics, higher individual parasite loads correlate with lower body condition scores and hematocrit, demonstrating that even under relatively good nutrition, parasitism still contributes measurably to variation in growth and health (Ortíz-Domínguez et al., 2024). Similar disease-related growth penalties are observed with systemic infections such as trypanosomiasis, contagious caprine pleuropneumonia, and peste des petits ruminants, which cause anemia, respiratory compromise, fetal losses, and increased kid mortality, cumulatively depressing herd productivity and slowing genetic and nutritional gains (Challaton et al., 2023). In intensive settings, poorly managed housing can further predispose goats to parasitic and infectious disease, leading to weight loss accompanied by hematological signs of stress and elevated parasite egg counts.

6.2 Disease prevention and immunization programs

Effective disease prevention programs are essential to protect the benefits of improved feeding strategies on growth. Broad reviews of small-ruminant systems in sub-Saharan Africa conclude that infectious diseases, together with poor nutrition and genetics, are the main causes of low productivity, and emphasize that herd health plans must prioritize control of GIN, major viral diseases, and key bacterial infections (Kimeli et al., 2025). Strategic anthelmintic use, improved grazing management, and nutritional support all help reduce the clinical expression of parasitism and sustain growth, but rising anthelmintic resistance and knowledge gaps about parasite epidemiology often limit control in practice. Meta-analysis shows that better energy and protein supply improves resilience and resistance to GIN infection, mitigating the growth-depressing effects of worm burden and supporting the argument that parasite control and nutrition should be managed together (Cei et al., 2018).

Vaccination against major transboundary and respiratory diseases is a cornerstone of preventive programs and has direct implications for growth. A scoping review of preventive veterinary interventions in sub-Saharan Africa found that vaccination against priority diseases such as PPR, pasteurellosis, and contagious pleuropneumonia was generally both effective and profitable, reducing morbidity and mortality and improving returns on investment in feed and other inputs (Nuvey et al., 2022). At the herd level, implementing vaccination and basic biosecurity was associated with steep declines in respiratory disease incidence in semi-intensively managed goats, illustrating how targeted immunization can translate into healthier animals and better growth performance over time (Atlı et al., 2025). Even where some vaccines cause transient reductions in daily gain, as observed after foot-and-mouth disease vaccination in Korean native goats, the long-term protection against outbreaks and trade losses outweighs these short-term setbacks, especially when supportive management is used to buffer temporary performance dips (Jo et al., 2014).

6.3 Biosecurity and sanitation management

Biosecurity and sanitation measures reduce the introduction and spread of pathogens that erode growth performance, and they complement both feeding and vaccination strategies. Good herd health and biosecurity programs aim to maximize production while lowering the incidence of preventable diseases through practices such as pre-purchase testing, quarantine of new arrivals, and strict control of animal movement. Clean housing, appropriate stocking densities, and proper manure handling limit the buildup and transmission of gastrointestinal and ectoparasites, thereby decreasing chronic production losses associated with subclinical infection and improving the response to nutritional improvements (Fthenakis and Papadopoulos, 2017). In extensive and semi-intensive systems, lack of biosecurity, poor hygiene, and inadequate health management have been linked to high burdens of parasitism and lameness, culminating in reduced growth, reproduction, and increased mortality despite the apparent environmental adaptability of goats (Sejian et al., 2021).

Sanitation and general farm management also influence the prevalence of vector-borne and reproductive pathogens that indirectly affect growth by causing abortions, weak kids, and chronic debilitation. Studies in tropical dry-forest systems demonstrate that herds with poorer infrastructure and less structured sanitary management experience higher seroprevalence of agents such as Neospora caninum and bluetongue virus, whereas larger herds with better facilities show lower infection levels, underscoring the role of housing, vector control, and waste management in disease ecology (Gutiérrez et al., 2024). Regular monitoring for zoonotic and production-limiting parasites, prompt treatment of clinically affected animals, and avoidance of practices like spreading fresh feces on pastures all contribute to reduced environmental contamination and lower reinfection rates. Integrating these biosecurity and sanitation measures with tailored nutrition and vaccination creates a health-oriented production system in which goats can express their genetic growth potential more fully.

7 Environmental Factors Affecting Growth Performance

7.1 Regulation of temperature, humidity, and light conditions

Thermal environment is one of the main external factors modulating feed intake, energy use, and thus growth performance in goats. When temperature-humidity index (THI) rises above comfort thresholds, goats show increased respiratory rate, heart rate, and skin temperature, reflecting a higher energetic cost of thermoregulation that diverts nutrients away from growth (Figure 3) (Zhou et al., 2023). Experimental exposure to stepwise combinations of higher temperature and relative humidity demonstrated that, at THI ranges above about 75-80, goats reduce behaviors related to metabolism (feeding and rumination) and shift toward behaviors that enhance evaporative cooling, such as panting and increased water intake. Under hot, humid tropical conditions, rectal and skin temperatures, respiration rate, and lying time increase, while dry matter intake declines, confirming that prolonged heat load depresses nutrient intake and growth even in heat-adapted breeds (Ali et al., 2023).

Maintaining environmental conditions within the thermoneutral range, or at least limiting time above critical THI, is therefore essential to protect growth response to improved feeding. Reviews of heat stress in goats indicate that, beyond reduced intake, chronic high temperatures alter endocrine and immune function, leading to impaired metabolic efficiency and increased disease susceptibility that further constrain performance (Gadzama et al., 2025). Goats are resilient to heat compared with other ruminants, but their productivity and welfare still deteriorate markedly once ambient temperatures exceed about 38 °C, especially when combined with high humidity that limits evaporative cooling (Stavetska et al., 2025). Managing diurnal variation by exploiting cooler night or early morning periods for feeding and activity can help offset reductions in daytime intake and mitigate negative energy balance in hot environments (Danso et al., 2024).

Light conditions also interact with growth and product yield, particularly in cashmere goats, where controlled short-day photoperiods have been used to manipulate fiber growth. In Shanbei white cashmere goats, reducing daily light exposure to seven hours increased annual cashmere production by about one-third, demonstrating the strong photoperiodic control of secondary hair growth (Cui et al., 2023). However, the same short-photoperiod system increased concentrations of harmful gases such as ammonia in the barn, implying that without adequate ventilation, air quality and health may be compromised despite gains in fiber output. For meat-oriented systems, providing natural or artificial shade reduces solar radiation and contributes to lowering heat load, supporting higher feed intake and growth rates under hot conditions.

7.2 Housing design and ventilation management

Housing design strongly influences the microclimate experienced by goats and thus the extent to which heat stress erodes the benefits of improved nutrition. Studies comparing different housing systems during hot–humid seasons show that modified sheds can reduce respiration rate and improve thermal comfort relative to conventional housing or fully open environments, even when rectal temperature remains within a narrow range across systems (Singh et al., 2023). Cross-ventilated barns and shade structures are highlighted as core environmental modifications, lowering heat load by reducing solar gain and facilitating convective and evaporative heat loss, which in turn helps sustain intake and productivity in hot climates (Gadzama et al., 2025). In contrast, fully confined "barn" systems with high stocking density and limited movement have been associated with weight loss, elevated stress indicators, and higher parasitic egg counts, indicating that poorly designed intensive housing can impair growth despite controlled feeding.

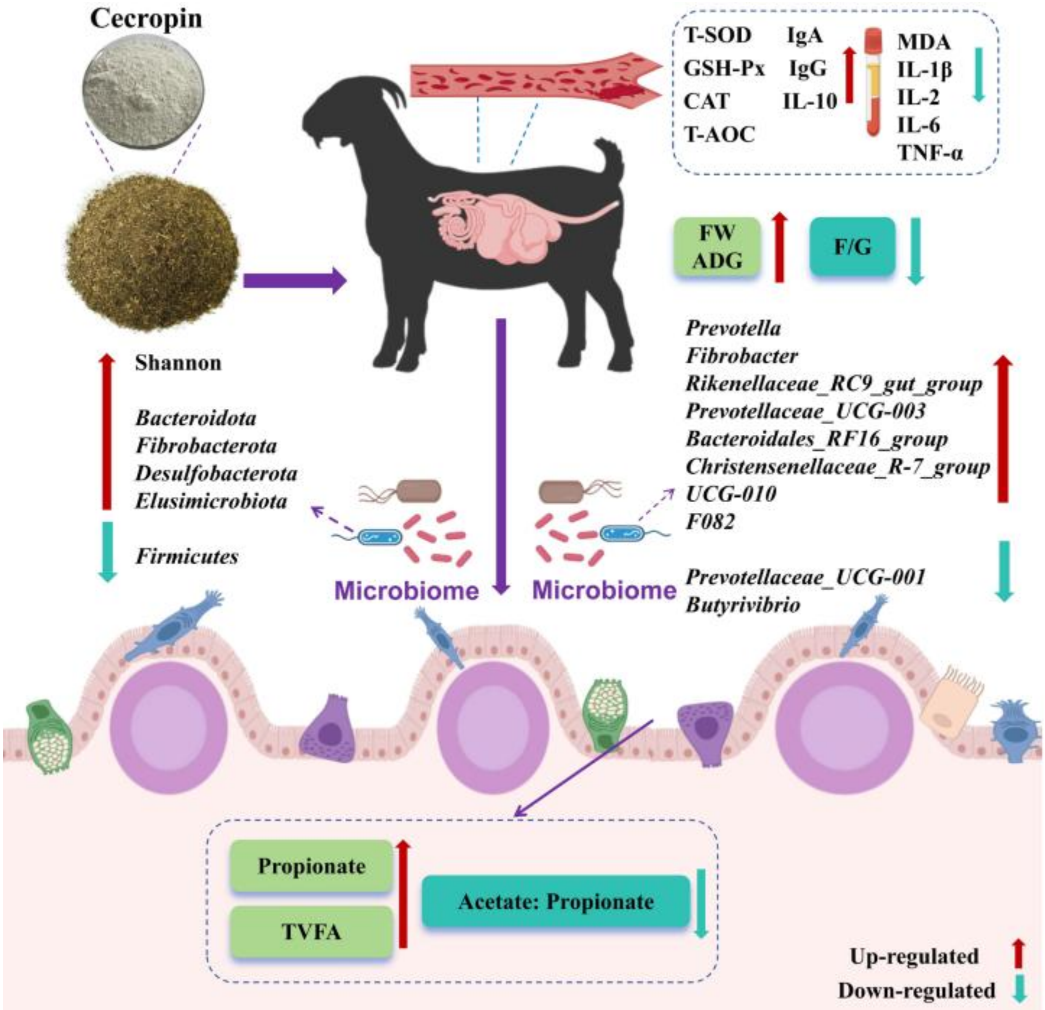

Figure 3 Mechanisms of the impact of dietary cecropin on the health of goats. T-SOD, total superoxide dismutase; GSH-Px, glutathione peroxidase; CAT, catalase; T-AOC, total antioxidant capacity; IgA, immunoglobulin A; IgG, immunoglobulin G; IL-10, interleukin-10; MDA, malondialdehyde; IL-1β, interleukin-1 beta; IL-2, interleukin-2; IL-6, interleukin-6; TNF-α, tumor necrosis factor-alpha; FW, final body weight; ADG, average daily gain; F/G, feed-to-gain ratio; TVFA, total volatile fatty acid (Adopted from Zhou et al., 2023)

Ventilation management is equally critical for maintaining both temperature-humidity balance and air quality. A review of the relationship between thermal environment and energy metabolism in goats emphasizes that, once ambient conditions exceed adaptive thresholds, respiratory frequency, evaporative heat loss, and rectal temperature rise sharply, underscoring the need for designs that promote airflow and heat dissipation (Lima et al., 2022). Monitoring temperature and humidity in real time, and adjusting wall openings or mechanical ventilation accordingly, allows farmers to keep THI below levels that trigger declines in metabolic behaviors and disruptions in endocrine status (Zhou et al., 2023). In dairy goat barns, Internet-of-Things monitoring of gases showed that building structure and the management of openings, together with litter replacement frequency, significantly affect concentrations of ammonia and carbon dioxide, and low winter THI even raised concerns about cold stress when openings were over-managed (Celozzi et al., 2025). These findings suggest that housing design and ventilation should be tuned seasonally to avoid both heat and cold stress, ensuring that feed resources are converted efficiently into growth.

7.3 Stress factors and mitigation strategies

Environmental, nutritional, and handling stressors interact to shape growth performance by altering behavior, physiology, and immune competence. Heat stress is often the dominant physical stressor in tropical and subtropical regions, where goats display behavioral adaptations such as shade seeking, nocturnal grazing, and reduced daytime feeding; while these responses help maintain homeothermy, they also decrease feeding efficiency and growth if not compensated by management. Under experimental hot environments, goats exhibit elevated rectal and skin temperatures, higher respiration rate, and reduced blood glucose, alongside lower dry matter intake but increased digestibility, indicating both a physiological strain and a metabolic adjustment that may not fully protect growth over longer periods (Ali et al., 2023). Reviews of climate change and goat production emphasize that high temperatures impair immune and endocrine systems, depressing growth, reproductive capacity, and product quality, which collectively lowers herd-level productivity unless mitigated by adapted management (Stavetska et al., 2025).

A variety of mitigation strategies can buffer goats against environmental and management-related stress, thereby preserving growth responses to improved feeding. Environmental strategies include providing shade, optimizing housing orientation, and installing cooling systems or misting where feasible, which have been shown to reduce heat load and lower key stress indicators such as respiratory rate and rectal temperature. Nutritional and rumen-oriented interventions, such as feeding antioxidants or specific probiotics, can also enhance resilience; for example, prophylactic supplementation with Clostridium butyricum and *Saccharomyces cerevisiae* before a heat-stress period improved average daily gain and feed efficiency by supporting rumen fermentation and antioxidant status under high THI (Xue et al., 2022). At the same time, good handling practices that minimize psychological and pre-slaughter stress are important, because goats are particularly susceptible to management-related stress during transport and lairage, which can depress performance and meat quality even when on-farm feeding is optimal (Kumar et al., 2022). Combining environmental control, targeted feeding strategies, and low-stress handling provides a comprehensive approach to mitigating stress and securing growth performance in modern goat systems.

8 Case Study: Analysis of Typical Feeding Strategies on Goat Growth Performance

8.1 Case of diet optimization in a large-scale farm

Diet optimization in commercial goat operations typically focuses on balancing local roughage resources with strategic concentrate supplementation to maximize average daily gain (ADG) and feed efficiency. An intensive trial with 32 Barbari male kids showed that increasing concentrate mix from 0.7% to 2.1% of body weight on a pulse-straw basal diet significantly improved weight gain, nutrient digestibility, rumen volatile fatty acid production, and nitrogen retention, providing a clear framework for intensive meat-oriented farms using crop residues as the main roughage (Dutta et al., 2025). In practice, such a strategy allows large farms to convert low-value chickpea straw and similar by-products into higher-value meat while maintaining acceptable health indicators, as reflected in improved blood glucose and hemoglobin profiles under higher concentrate inclusion.

On-farm diet optimization for replacement females illustrates how modifying existing rations can enhance future herd productivity in semi-commercial settings. In a Malaysian smallholder but fully intensive system, 4-month-old Boer-cross replacement does fed a reformulated ration based on NRC recommendations, using the same local forages and agro-industrial by-products as the farmer’s original diet but at higher quantity and better nutrient balance, achieved markedly higher final body weight and ADG than goats on the routine feeding program (Ghani et al., 2017). After seven months, treated goats reached about 39 kg versus 32 kg in controls, and a higher proportion achieved a body condition score ≥3, demonstrating how technically guided ration formulation within existing feed resources can lift growth performance and readiness for breeding in a quasi-large-scale scenario.

8.2 Comparative analysis of growth performance under different feeding systems

Comparisons among feeding systems consistently show that intensive or supplemented systems support higher growth rates than unsupplemented grazing, though at the cost of greater input use. A review of feeding systems in sheep and goats concluded that kids and lambs finished on pasture alone have lower ADG and carcass yield than those finished in stalls or on pasture plus concentrate, while supplemented grazing animals often achieve performance comparable to, or better than, fully stall-fed counterparts (Ke et al., 2023). These patterns reflect both increased energy and protein density and more stable nutrient supply, underscoring why semi-intensive systems with targeted supplementation are often recommended for improving growth while retaining some grazing-based advantages (Huang et al., 2023).

Field comparisons confirm these general trends under smallholder conditions. In Assam local goats, kids reared intensively with ad libitum concentrate and fodder exhibited significantly higher final body weights and superior feed conversion efficiency compared with contemporaries managed extensively with traditional grazing and browsing, with divergence in body weight becoming highly significant from the third week onward (Hoque et al., 2020). Similarly, work on Osmanabadi goats comparing traditional grazing with various stall-feeding plus supplementation methods found that systems combining grazing with stall feeding achieved the best overall body growth and chest girth development, suggesting that integrating controlled feeding with natural browsing can yield both biological and economic benefits over purely extensive methods (Da et al., 2021).

8.3 Evaluation of technical interventions (Additives/Management Measures)

Feed additives and formulation technologies offer additional leverage to enhance growth performance beyond basal ration design. A meta-analysis of *Saccharomyces cerevisiae* supplementation in growing goats found that dietary yeast consistently increased ADG while only modestly affecting dry-matter intake and feed conversion ratio, and also elevated blood glucose, white blood cell counts, and ruminal propionate and total volatile fatty acids, indicating improved rumen fermentation and health status (Ogbuewu and Mbajiorgu, 2023). Similarly, a factorial trial with neem leaf and polyethylene glycol showed that adding 6% neem leaf plus 15% PEG to the concentrate raised feed intake, nutrient digestibility, ADG, and propionic acid concentration while reducing ruminal methanogens and protozoa, suggesting that certain plant-based additives can simultaneously enhance growth and modulate the rumen microbiome in a favorable direction (Taethaisong et al., 2023).

Management-type technical interventions, such as pelleting and optimizing concentrate level, can also markedly improve growth efficiency in commercial settings. A comparative on-farm study in Bangladesh demonstrated that a complete pelleted feed (40% roughage, 60% concentrate) under stall feeding produced substantially higher daily weight gain and lower feed conversion ratio and cost per kilogram gain than conventional semi-intensive feeding without pellets, implying strong economic incentives for pelleting where infrastructure allows (Ahmed et al., 2020). Likewise, trials in India and Iraq indicate that intermediate concentrate levels around 2%-3% of body weight, whether in mash or pelleted form, often yield superior growth and feed efficiency compared with lower or higher levels, helping define practical targets for intensive fattening systems (Al-Ani, 2024; Dutta et al., 2025). Together, these technical interventions—microbial and plant additives, precision in concentrate level, and physical processing of feeds—provide a toolkit for fine-tuning feeding strategies to maximize growth performance in goats under diverse production environments.

9 Conclusion and Prospects

Research on feeding strategies for goats consistently demonstrates that growth performance is highly responsive to both nutrient density and ration structure. Optimally balanced diets that match energy and protein to physiological stage, breed, and production objectives improve average daily gain, feed conversion ratio, and carcass traits. Appropriate use of high-quality forages, combined with concentrates formulated to support rumen health, underpins efficient growth while reducing digestive upsets. Strategic supplementation with minerals and vitamins further supports skeletal development, immune competence, and overall robustness, especially in intensive or semi-intensive systems. Studies comparing different management systems indicate that integrating good nutrition with appropriate housing, health programs, and environmental control yields additive benefits for growth. Intensive and semi-intensive systems, when properly managed, enable more precise feed allocation and better control of environmental stressors, leading to more uniform growth rates. Genetic improvement and targeted breeding add another layer of enhancement by improving feed efficiency, growth potential, and resilience, particularly when combined with modern tools such as marker-assisted selection. Overall, the literature converges on the view that growth in goats is maximized when feeding strategies are designed holistically, aligning diet formulation, management, health, genetics, and environment.

Despite substantial progress, existing studies on feeding strategies for goats exhibit several methodological and contextual limitations. Many experiments are short-term and focus on immediate growth responses rather than lifetime performance, carcass quality, or long-term health outcomes. Sample sizes are often modest, and experimental conditions may not reflect the diversity of real-world production systems, especially in smallholder or resource-limited settings. Furthermore, results generated in one breed or cross are commonly extrapolated to others without rigorously accounting for genetic and physiological differences. This reduces the generalizability of reported feeding recommendations. There is also a lack of standardized protocols for evaluating growth performance and feed efficiency, complicating comparisons across studies and meta-analyses. Economic assessments, including cost–benefit analyses of feed interventions, are frequently underdeveloped or omitted, limiting the practical applicability for farmers and advisors. Environmental dimensions, such as greenhouse gas emissions, nutrient excretion, and resource use efficiency, are not consistently integrated into feeding trials. Finally, interactions among nutrition, disease dynamics, housing design, and climate-related stress are often studied in isolation, leaving important knowledge gaps on how combined interventions influence growth and sustainability.

Future research on feeding strategies for goats is likely to move toward more integrated, systems-based approaches that address productivity, animal welfare, economic viability, and environmental impact simultaneously. There is a growing need for long-term, multi-site trials that examine how diet formulation, feeding frequency, and management practices perform across different breeds, climates, and production scales. Precision nutrition, supported by digital tools and sensor technologies, offers promising avenues for tailoring diets to individual animals or groups based on real-time assessment of growth, health, and behavior. These approaches could help optimize feed use efficiency while reducing waste and environmental footprints. Another important trend is the incorporation of genomic and molecular tools into nutrition research, enabling better understanding of how genetic variation shapes responses to different diets. This will support breeding programs that explicitly select for traits such as feed efficiency, resilience to nutritional stress, and adaptability to alternative or locally available feed resources. Research on functional feeds, including plant bioactives, probiotics, and other additives, should increasingly focus on their combined effects with management and environmental interventions rather than in isolation. Ultimately, development of context-specific, evidence-based feeding guidelines that consider local feed availability, climate risks, and market demands will be essential for translating scientific advances into practical gains in goat growth performance worldwide.

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Conflict of Interest Disclosure

The author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

References

Abdelsattar M., Zhao W., Diaby M., Vargas-Bello-Pérez E., and Zhang N., 2025, Recent nutritional strategies and feed additives to stimulate proper rumen development in young goats, Translational Animal Science, 9: txae164.
https://doi.org/10.1093/tas/txae164

Ahmad N., Ali A., Abdullah M., Khalique A., Javed K., Bhatti J.A., Ahmad S., Saima S., Iqbal Z., Omer M.O., Younas U., Iqbal Z.M., Anjum K.M., Hussain T., and Shahzad F., 2014, Effect of feeding frequency on the growth performance of Beetal goat kids during winter season, Journal of Animal and Plant Sciences, 24(Suppl.1): 73-76.

Ahmed S., Rakib M., Hemayet M., Roy B., and Jahan N., 2020, Effect of complete pellet feed on commercial goat production under the stall feeding system in Bangladesh, Journal of Advanced Veterinary and Animal Research, 7: 704-709.
https://doi.org/10.5455/javar.2020.g471

Ali A., Sandi S., Fariani A., and Darussalam A., 2023, Physiological changes and behavioral responses in heat-stressed goats under humid tropical environment, International Journal of Biometeorology, 67: 1757-1764.
https://doi.org/10.1007/s00484-023-02536-x

Ali A.I.M., Sandi S., Sahara E., Rofiq M.N., and Dahlanuddin D., 2022, Effects of acid drinking water on nutrient utilization, water balance, and growth of goats under hot-humid tropical environment, Small Ruminant Research, 210: 106689.
https://doi.org/10.1016/j.smallrumres.2022.106689

Atlı F., Kandemir Ç., Taşkın T., and Şentürk S., 2025, Change of diseases in semi-intensively raised Saanen goats by year in İzmir, Osmaniye Korkut Ata University Journal of the Institute of Science and Technology, 8(3): 1000-1008.
https://doi.org/10.47495/okufbed.1571270

Aziz H.A., Nassar M.S., and Badawy H.M., 2018, Rumen fermentations and rumen ciliate protozoa of goat kids fed diets with different concentrate: roughage ratio, Egyptian Journal of Nutrition and Feeds, 21(2): 417-430.
https://doi.org/10.21608/ejnf.2018.75770

Bhinder M., Nayyar S., Singh C., and Singla M., 2024, An approach to evaluate growth performance and health status of Beetal goat kids born under stall-fed and free-range grazing system during summer and winter, Biological Rhythm Research, 55: 474-489.
https://doi.org/10.1080/09291016.2024.2419804

Cai L., Yu J., Hartanto R., and Qi D., 2021, Dietary supplementation with *Saccharomyces cerevisiae*, Clostridium butyricum and their combination ameliorate rumen fermentation and growth performance of heat-stressed goats, Animals, 11: 2116.
https://doi.org/10.3390/ani11072116

Cei W., Salah N., Alexandre G., Bambou J.C., and Archimède H., 2018, Impact of energy and protein on the gastro-intestinal parasitism of small ruminants: a meta-analysis, Livestock Science, 212: 34-44.
https://doi.org/10.1016/j.livsci.2018.03.015

Celozzi S., Ambrosini R., Rapetti L., Mattiello S., and Finzi A., 2025, IoT monitoring of indoor air quality in dairy goat barns: the role of building characteristics and litter management, Animals, 15: 3332.
https://doi.org/10.3390/ani15223332

Challaton K.P., Boko K.C., Akouedegni C.G., Alowanou G.G., Kifouly A.H., and Hounzangbé-Adoté M.S., 2023, Common infectious and parasitic diseases in goats of tropical Africa and their impacts on production performance: a review, World's Veterinary Journal, 13(3): 425-440.
https://doi.org/10.54203/scil.2023.wvj47

Chavala B.C., Kifaro G.C., Tungu G.B., and Chasama G.L., 2023, Genetic parameters for growth traits of Malya goats and heterosis from crossbreds of Malya and Sukuma goats, Asian Journal of Research in Animal and Veterinary Sciences, 6(4): 492-502.
https://doi.org/10.9734/ajravs/2023/v6i4277

Cui W., Lin C., Liu Y., Qiu Z., Gao W., Wang C., Chen Y., and Yang Y., 2023, Effect of controlling light on cashmere growth and harmful gas parameters in Shanbei white cashmere goats, Animals, 13: 995.
https://doi.org/10.3390/ani13060995

Suresh B.N., Jaishankar N., Thirumalesh, and Ramesh B.K., 2013, Performance of Osmanabadi goat kids under different feeding regimes, Research Journal of Agricultural Sciences, 4(2): 303-304.
https://doi.org/10.22271/veterinary.2021.v6.i1a.554

Danso F., Iddrisu L., Lungu S., Zhou G., and Ju X., 2024, Effects of heat stress on goat production and mitigating strategies: a review, Animals, 14: 1793.
https://doi.org/10.3390/ani14121793

Dutta T.K., Sheoran M., Chatterjee A., Tripathi P., and Mohammad A., 2025, Optimizing performance in young goats: impact of concentrate supplementation in Cicer arietinum straw-based diets on rumen fermentation, nutrient availability, blood profile and growth, Tropical Animal Health and Production, 57(4): 208.
https://doi.org/10.1007/s11250-025-04435-2

Fthenakis G.C., and Papadopoulos E., 2017, Impact of parasitism in goat production, Small Ruminant Research, 152: 63-68.
https://doi.org/10.1016/j.smallrumres.2017.04.001

Gadzama I.U., Hina Q., Ray S., Asadi H., Mugeniwayesu C., and Panuel P., 2025, Heat stress in goat (Capra hircus): impacts on physiological responses, production, and reproduction, Zhivotnovadni Nauki (Bulgarian Journal of Animal Science), 62(4): 17-36.
https://doi.org/10.61308/odqj2543

Ghani A., Shahudin M., Zamri-Saad M., Zuki A., Wahid H., Kasim A., Salisi M., and Hassim H., 2017, Enhancing the growth performance of replacement female breeder goats through modification of feeding program, Veterinary World, 10: 630-635.
https://doi.org/10.14202/vetworld.2017.630-635

Guo J.Z., Tao H.X., Li P.F., Li L., Zhong T., Wang L.J., Ma J.Y., Chen X.Y., Song T.Z., and Zhang H.P., 2018, Whole-genome sequencing reveals selection signatures associated with important traits in six goat breeds, Scientific Reports, 8(1): 10405.
https://doi.org/10.1038/s41598-018-28719-w

Gutiérrez L., Alva G., Godoy D., Frias H., Arista M., Bardales W., Encina R., Portocarrero S., Saucedo J., Cruz J., and Murga N., 2024, Impact of production practices and sanitary management on the prevalence of Neospora caninum and bluetongue virus in Creole goats from the tropical dry forest of Utcubamba, Peru, American Journal of Veterinary Research, 86(1): 1-8.
https://doi.org/10.2460/ajvr.24.08.0238

Guyo M., Melesse A., and Taye M., 2023, On-farm growth performance evaluations of kids born from Arsi-Bale goats in three agro-ecologies of Bale Zone, Ethiopia, African Journal of Food, Agriculture, Nutrition and Development, 23(4): 23161-23179.
https://doi.org/10.18697/ajfand.119.22820

Hoque J., Deka R., Sarma N., Ahmed H., and Laskar S., 2020, Growth response of Assam local goats under intensive farming, Agricultural Science Digest - A Research Journal, 2021: 41.
https://doi.org/10.18805/ag.d-5173

Huang J., Jiao S., Fu Y., Zhao W., Diao Q., Tian T., and Zhang N., 2024, Effect of feeding level on growth and slaughter performance, and allometric growth of tissues and organs in female growing Saanen dairy goats, Animals, 14: 730.
https://doi.org/10.3390/ani14050730

Huang Y., Liu L., Zhao M., Zhang X., Chen J., Zhang Z., Cheng X., and Ren C., 2023, Feeding regimens affecting carcass and quality attributes of sheep and goat meat — a comprehensive review, Animal Bioscience, 36: 1314-1326.
https://doi.org/10.5713/ab.23.0051

Jeyakumar M., 2020, Different feeding systems on growth performance in Kanni Adu goats of Tamil Nadu, Journal of Entomology and Zoology Studies, 8(6): 2098-2100.
https://doi.org/10.22271/j.ento.2020.v8.i6ab.8765

Jo N., Jung J., Kim J., Lee J., Jeong S., Kim W., Sung H., and Seo S., 2014, Effect of vaccination against foot-and-mouth disease on growth performance of Korean native goat (Capra hircus coreanae), Journal of Animal Science, 92(6): 2578-2586.
https://doi.org/10.2527/jas.2014-7190

Ke T., Zhao M., Zhang X., Cheng Y., Sun Y., Wang P., Ren C., Cheng X., Zhang Z., and Huang Y., 2023, Review of feeding systems affecting production, carcass attributes, and meat quality of ovine and caprine species, Life, 13: 1215.
https://doi.org/10.3390/life13051215

Kimeli P., Mwacalimba K., Tiernan R., Mijten E., Miroshnychenko T., and Nautrup P., 2025, Important diseases of small ruminants in sub-Saharan Africa: a review with a focus on current strategies for treatment and control in smallholder systems, Animals, 15: 706.
https://doi.org/10.3390/ani15050706

Kumar P., Abubakar A., Ahmed M., Hayat M., Kaka U., Pateiro M., Sazili A., Hoffman L., and Lorenzo J., 2022, Pre-slaughter stress mitigation in goats: prospects and challenges, Meat Science, 195: 109010.
https://doi.org/10.1016/j.meatsci.2022.109010

Lima A., Silveira R., Castro M., De Vecchi L., Fernandes M., and Resende K., 2022, Relationship between thermal environment, thermoregulatory responses and energy metabolism in goats: a comprehensive review, Journal of Thermal Biology, 109: 103324.
https://doi.org/10.1016/j.jtherbio.2022.103324

Lin X., Ju L., Cheng Q., Jiang Y., Hou Q., Hu Z., Wang Y., and Wang Z., 2023, Comparison of growth performance and rumen metabolic pathways in sheep and goats under the same feeding pattern, Frontiers in Veterinary Science, 10: 1013252.
https://doi.org/10.3389/fvets.2023.1013252

Liu Y., Xi H., Xu Q., Zhou B., Li J., Su R., Lü Q., Zhang Y., Wang R., and Wang Z., 2025, Genome-wide association study of copy number variation and early growth traits in Inner Mongolian cashmere goats, Frontiers in Veterinary Science, 12: 1651622.
https://doi.org/10.3389/fvets.2025.1651622

Lu C., and Potchoiba M., 1990, Feed intake and weight gain of growing goats fed diets of various energy and protein levels, Journal of Animal Science, 68(6): 1751-1759.
https://doi.org/10.2527/1990.6861751x

Lu J., Chen Z., Chen P., Li Z., Wan Y., Song Y., Wang F., and Zhang Y., 2022, Dietary potential probiotics and enzymes complex modulates the performance and rumen microbiota in weaned goats, Journal of Applied Microbiology, 134(2): lxac079.
https://doi.org/10.1093/jambio/lxac079

Lu J., Chen Z., Gao Q., Li P., Wang J., Cai Y., Wang Z., Li D., Li H., Wang F., and Zhang Y., 2021, Combined supplementation of probiotics and enzymes improves performance and regulates rumen microbiota in fattening goats, Animal Bioscience.
https://doi.org/10.21203/rs.3.rs-1043297/v1

Lu J., Chen Z., Wang F., Lu H., and Zhang Y., 2025, Combined supplementation with probiotics and enzymes regulates the performance and microbiota of goats, Animal Bioscience.
https://doi.org/10.5713/ab.25.0134

Moaeen-Ud-Din M., Muner R., and Khan M., 2022, Genome wide association study identifies novel candidate genes for growth and body conformation traits in goats, Scientific Reports, 12(1): 9891.
https://doi.org/10.1038/s41598-022-14018-y

Moniruzzaman M., Hashem M., Akhter S., and Hossain M., 2002, Effect of feeding systems on feed intake, eating behavior, growth, reproductive performance and parasitic infestation of Black Bengal goat, Asian-Australasian Journal of Animal Sciences, 15: 1453-1457.
https://doi.org/10.5713/ajas.2002.1453

Mpendulo C., Akinmoladun O., Ikusika O., and Chimonyo M., 2020, Effect of hydric stress on intake, growth performance and nutritional status of Nguni goats, Italian Journal of Animal Science, 19: 1071-1078.
https://doi.org/10.1080/1828051x.2020.1819897

Mpendulo C., Chimonyo M., and Zindove T., 2017, Influence of water restriction and salinity on feed intake and growth performance of Nguni does, Small Ruminant Research, 149: 112-114.
https://doi.org/10.1016/j.smallrumres.2017.02.002

Mucha S., Tortereau F., Doeschl-Wilson A., Rupp R., and Conington J., 2022, Animal Board invited review: meta-analysis of genetic parameters for resilience and efficiency traits in goats and sheep, Animal, 16(3): 100456.
https://doi.org/10.1016/j.animal.2022.100456

Mugoti A., Nyamukanza C., Munengwa A., Moyo S., and Chikumba N., 2025, Effects of climate change on goat production and mitigatory measures in semiarid savanna ecosystems, Journal of Integrative Environmental Sciences, 22(1): 2513899.
https://doi.org/10.1080/1943815x.2025.2513899

Ncube K., Nephawe K., Mpofu T., Monareng N., Mofokeng M., and Mtileni B., 2025, Genomic advancements in assessing growth performance, meat quality, and carcass characteristics of goats in sub-Saharan Africa: a systematic review, International Journal of Molecular Sciences, 26: 52323.
https://doi.org/10.3390/ijms26052323

Nuvey F., Arkoazi J., Hattendorf J., Mensah G., Addo K., Fink G., Zinsstag J., and Bonfoh B., 2022, Effectiveness and profitability of preventive veterinary interventions in controlling infectious diseases of ruminant livestock in sub-Saharan Africa: a scoping review, BMC Veterinary Research, 18(1): 332.
https://doi.org/10.1186/s12917-022-03428-9

Ofori S., and Hagan J., 2020, Genetic and non-genetic factors influencing the performance of the West African dwarf goat kept at the Kintampo goat breeding station of Ghana, Tropical Animal Health and Production, 52: 2577-2584.
https://doi.org/10.1007/s11250-020-02276-9

Ogbuewu I., and Mbajiorgu C., 2023, Meta-analysis of *Saccharomyces cerevisiae* on enhancement of growth performance, rumen fermentation and haemato-biochemical characteristics of growing goats, Heliyon, 9: e14178.
https://doi.org/10.1016/j.heliyon.2023.e14178

Omotoso O.B., Adebisi A.A., Olufemi-Amodu B., and Fajemisin A.N., 2022, Effect of feeding frequency of *Curcuma longa* supplemented diets on nutrients intake, growth performance and rumen fermentation characteristics of goats, Acta Fytotechnica et Zootechnica, 25(3): 185-193.
https://doi.org/10.15414/afz.2022.25.03.185-193

Ortíz-Domínguez G., González-Pech P., Torres-Acosta J., Ventura-Cordero J., Villalba J., and Sandoval-Castro C., 2024, Relevance of individual data when assessing the gastrointestinal nematode infection level, nutritional and productive variables in a tropical farm context: the median isn't the message, Animals, 14: 603.
https://doi.org/10.3390/ani14040603

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Influence of Canopy Structure on Photosynthesis and Fruit Quality in Grapevines

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Abstract Canopy structure plays a critical role in regulating light distribution, photosynthetic efficiency, and ultimately fruit quality in grapevines. This study systematically reviews the characteristics of different canopy architectures and their effects on the vineyard light environment. It further analyzes how variations in canopy density and spatial configuration influence leaf photosynthesis, including differences among canopy layers and the accumulation and transport of photosynthates. The relationship between canopy structure and key fruit quality parameters, such as sugar content, organic acids, and secondary metabolites, is also discussed. In addition, common canopy management practices, including pruning, leaf removal, and training systems, are evaluated for their effectiveness in optimizing canopy microclimate. Case studies comparing different training systems and management strategies highlight practical approaches to improving grape quality. The interactions between canopy structure and environmental factors, such as light, water, and nutrients, are also addressed. Overall, this study provides a theoretical basis and practical guidance for optimizing canopy structure to enhance grapevine productivity and fruit quality.
Keywords Canopy structure; Grapevine; Photosynthesis; Fruit quality; Canopy management

1 Introduction

Grapevine canopy structure governs how light, temperature, and air flow are distributed within the vine, thereby regulating photosynthesis, carbon balance, and berry development. Light interception and its spatial distribution strongly affect sugar accumulation, acidity, color, and aroma compounds that define grape and wine quality. In the context of climate change and increasingly warm, dry regions, refining canopy architecture has become a key strategy to maintain productivity and fruit quality while moderating excessive heat and radiation loads (Torres et al., 2020; Pallotti et al., 2025). Understanding how specific structural features of the canopy translate into physiological responses and fruit composition is therefore of both scientific and practical importance (Zhu et al., 2021).

Biomass production and yield potential are closely related to the amount of solar radiation intercepted by the foliage, while grape composition depends on the exposure of leaves and clusters to light within the canopy microclimate. Excessive shading reduces photosynthesis and is linked to poor grape and wine quality, whereas overly open canopies may induce overheating, sunburn, and degradation of acids and phenolics (Torres et al., 2020). Canopy management practices such as leaf removal, shoot thinning, and crop load adjustments are widely used to balance source–sink relationships, control microclimate, and optimize ripening. Recent work shows that canopy size and architecture largely determine whole-plant carbon gain, the speed of ripening, and the allocation of non-structural carbohydrates, often more strongly than crop level itself. Consequently, quantitative knowledge of how canopy structure shapes photosynthetic efficiency and berry composition is essential for designing training systems and management strategies adapted to diverse climates (Zhu et al., 2021; Del Zozzo et al., 2024).

Internationally, detailed studies have linked canopy geometry, light interception, and grape quality using field measurements, 3D digitizing, and radiation models. Structural indices and light microclimate variables explain variation in sugars, anthocyanins, and phenolics, and demonstrate that canopy division and shoot orientation are major determinants of bunch exposure. Whole-canopy gas exchange and training-system comparisons indicate that canopy geometry affects net CO_2 exchange, transpiration, drought resilience, and final fruit maturity, with some systems showing higher photosynthetic efficiency under water deficit. Manipulations of canopy porosity and solar exposure via leaf removal and shoot thinning reveal complex, compound-specific responses of flavonoid groups and methoxypyrazines, and highlight economic trade-offs between improved maturity and higher labor costs. At the same time, microclimate studies within clusters and along row orientations show that the timing and intensity of radiation and berry temperature strongly modulate anthocyanin profiles, phenolic content, and volatile composition, with overexposure often detrimental in hot, high-radiation environments. More recently, source-sink adjustment experiments and carbon-limitation treatments have clarified how leaf area and canopy architecture regulate sugar and anthocyanin accumulation, as well as reserve carbohydrates and carry-over effects across seasons (Escalona et al., 2020; Wang et al., 2022). Despite these advances, there remains a need for integrative work directly linking measurable canopy structural traits to spatial patterns of photosynthesis within the canopy and to detailed berry quality parameters across contrasting environments.

Building on this body of work, the present study titled “Influence of Canopy Structure on Photosynthesis and Fruit Quality in Grapevines” aims to clarify the functional links between canopy architecture, leaf-level and canopy-scale photosynthesis, and grape quality attributes. The first objective is to quantify how different canopy structures-defined by parameters such as leaf area index, porosity, vertical and lateral distribution of foliage, and training configuration-affect light interception, within-canopy light gradients, and gas-exchange characteristics under field conditions. A second objective is to relate these structural and physiological variables to key fruit quality metrics, including sugars, acidity, phenolic composition (especially anthocyanins and flavonols), and selected aroma-relevant metabolites, across ripening. A third objective is to evaluate how canopy structural manipulation can be used as a practical tool to balance source–sink status and microclimate, with particular attention to warm or water-limited sites where excessive radiation and heat can compromise color and flavor. To achieve these aims, the study will combine quantitative characterization of canopy structure (e.g., geometric or imaging-based indices), measurements of light microclimate and whole-canopy or segment-level photosynthesis, and detailed berry composition analyses. By integrating structural, physiological, and compositional data, the study seeks to provide a mechanistic framework that can guide the design and management of grapevine canopies to optimize both photosynthetic performance and fruit quality under current and future growing conditions.

2 Basic Concepts and Types of Canopy Structure

2.1 Definition and components of canopy structure

Canopy structure encompasses the shape, volume, and spatial arrangement of foliage and woody organs, including shoot path, foliage envelope, and leaf orientation (Louarn et al., 2007). Grapevine canopies are discontinuous and heterogeneous, so parameters such as leaf area density (LAD), leaf inclination, and azimuth are used to characterize their 3D distribution (Mabrouk et al., 2015). This structure controls light gradients within the canopy, affecting stomatal behavior and photosynthetic activity from the outer sunlit leaves to the shaded interior.

Structural components are strongly influenced by training and trellis design, which determine shoot positioning, canopy height, and the division or concentration of foliage (Louarn et al., 2008). Canopy density in the fruiting zone, expressed as leaf layer number or LAD, governs light quantity and quality around clusters, with high densities driving photosynthetic photon flux density (PPFD) below 1%-5% of ambient. The balance between exposed and interior leaf area is therefore a central feature of canopy structure (Reynolds and Heuvel, 2009).

2.2 Common grapevine canopy types

Vertical shoot positioned (VSP) systems arrange shoots upright along catch wires, producing a relatively narrow, dense curtain with high average LAD, especially near the fruit zone (Gladstone and Dokoozlian, 2003). In Cabernet Sauvignon, two-wire VSP systems can exceed 8-10 m^2 leaf area per meter of canopy, sharply reducing fruit-zone PPFD and increasing leaf layer number. VSP canopies are widely adopted but often require leaf removal or shoot thinning to maintain suitable light in the cluster region (Louarn et al., 2008).

Pergola and other high-wire or divided systems (e.g., lyre, Geneva Double Curtain, single-curtain) spread foliage over a larger volume, frequently reducing local density and modifying microclimate. Pergola structures may limit vigor by distributing shoots horizontally, whereas single-curtain systems can increase cluster light, photosynthesis, and assimilate allocation to fruit (Du et al., 2023). Divided and non-positioned systems often show high LAD in the outer shell and lower LAD inside, supporting better fruit-zone exposure at comparable total leaf area (Mabrouk et al., 2015).

2.3 Evaluation indicators of canopy structure

Leaf area index (LAI) and related descriptors are core indicators linking canopy structure to function. LAI and plant area index (PAI) are used to estimate canopy growth, light interception, and water requirements, and can now be obtained indirectly from smartphone apps (e.g., VitiCanopy) and point-quadrat methods. UAV-derived 3D point clouds and Sentinel-2 LAI time series enable plot-scale and seasonal mapping of LAI, canopy thickness, and leaf density distribution along the canopy wall (Comba et al., 2019; Abubakar et al., 2023).

Light interception and microclimate metrics complement area-based indices. PPFD and red:far-red ratios measured in the fruit zone decrease sharply as leaf area per meter of canopy or LAD increases, defining thresholds for “low” and “high” density canopies (Gladstone and Dokoozlian, 2003). Indirect metrics such as leaf layer number, canopy porosity, percent sunlit area, and atmometer evaporation are closely correlated with fruit-zone PPFD and are now obtainable with on-the-go RGB imaging or simple gap analysis. Together, LAI/LAD and light-based indicators describe how canopy architecture governs photosynthesis and fruit exposure.

Grapevine canopy structure integrates canopy shape, foliage distribution, and shoot architecture, all of which regulate light interception and microclimate around leaves and clusters. VSP, pergola, and divided canopies differ markedly in density patterns and fruit-zone exposure, so training choice is a primary lever for managing photosynthesis and berry composition. Quantitative indicators such as LAI, LAD, leaf layer number, porosity, and PPFD provide practical tools to evaluate and optimize canopy structure for both productivity and fruit quality.

3 Regulatory Mechanisms of Canopy Structure on Light Environment

3.1 Characteristics of light distribution and spatial heterogeneity

Light within grapevine canopies is highly stratified, with strong vertical and horizontal gradients. Measurements along transects show photosynthetic photon flux density (PPFD) and red:far-red ratio decrease sharply from the canopy exterior toward the fruit zone and centre, then increase again closer to the ground. This pattern generates a narrow interior region where PPFD and sunflecks reach their lowest values, while upper and outer layers intercept most of the incoming radiation. Three-dimensional reconstructions similarly indicate that only a minority of leaves capture the majority of intercepted light, leaving extensive shaded leaf area deep in the canopy (Iandolino et al., 2013).

This uneven light field produces marked spatial heterogeneity in leaf function and microclimate. In dense canopies, as much as half of the leaf area can remain in constant shade, with a small proportion of outer leaves absorbing most direct radiation. Inner leaves often operate at very low radiation levels and contribute little to net carbon gain, while exposed leaves experience higher temperatures and transpiration (Escalona et al., 2020). Row orientation further modifies spatial patterns, with different sides and zones of the canopy receiving contrasting radiation regimes over the day and season (Hunter et al., 2020). Such heterogeneity underpins within-canopy differences in photosynthesis, water status, and ultimately berry composition.

3.2 Effects of canopy density on light interception and transmission

Canopy density, commonly quantified as leaf area density or leaf area per row length, is a primary determinant of fruit-zone and interior light. Field surveys show that when leaf area exceeds about 8 m^2 m^{-1} of canopy length, fruit-zone PPFD can fall to ≤1% of ambient and red:far-red ratio to about 10% of ambient; at ≤4 m^2 m^{-1}, these values remain ≥5%-10% of ambient. Similar relationships were observed for fruit-zone PPFD and sunflecks, which decline sharply as leaf area density increases beyond moderate levels. In non-positioned systems, small increases in leaf area density between 2 and 4 m^2 m^{-3} cause steep reductions in fruit-zone PPFD before the decline levels off at higher densities (Gladstone and Dokoozlian, 2003).

Different training and trellis systems express canopy density in distinct spatial patterns, altering light interception and transmission. Shoot-positioned systems tend to concentrate higher leaf area density near the fruit zone, yet can maintain relatively higher fruit-zone light at a given density by reducing leaf layer number and improving exposure geometry (Figure 1) (Gladstone and Dokoozlian, 2003). Divided canopies, such as lyre or Geneva double curtain, achieve more even light penetration by splitting the foliage wall, lowering leaf layer number and slowing the decline of PPFD with rising density. Indices such as leaf layer number, exposed leaf area, and porosity integrate these effects and correlate closely with interior PPFD, making them useful tools to assess functional canopy density (Shtirbu et al., 2022).

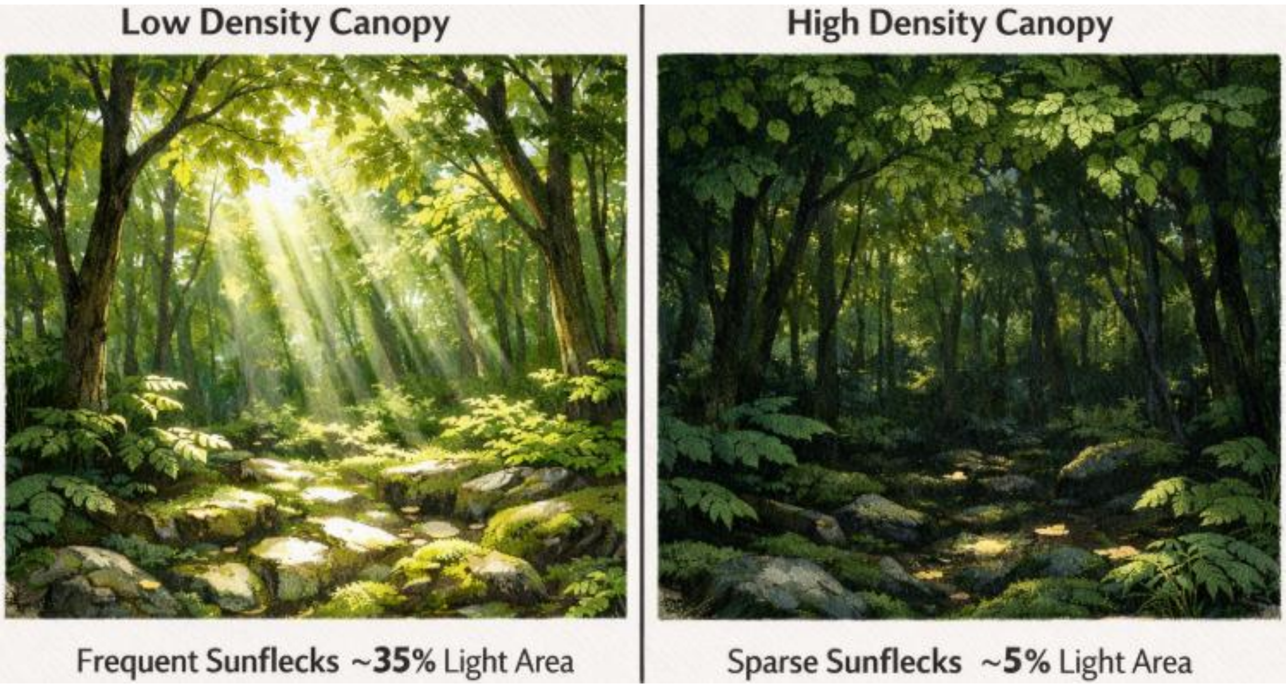

Figure 1 Comparison of sunfleck distribution under low and high canopy density, illustrating reduced light penetration with increased leaf area density (Adopted from Gladstone and Dokoozlian, 2003)

3.3 Improvement of light use efficiency through canopy optimization

Optimizing canopy architecture aims to balance total light interception with its distribution to maximize light use efficiency (LUE) at leaf and canopy scales. Three-dimensional and functional-structural models show that a relatively small proportion of leaves (20%-30%) can intercept roughly 80% of absorbed light, implying substantial scope to reduce unproductive shaded leaf area without sacrificing total interception (Iandolino et al., 2013; Prieto et al., 2019). Simulated and measured canopies with more favorable leaf area density and leaf orientation achieve similar or higher absorbed light with less total leaf area, thus improving radiation use efficiency and whole-canopy carbon gain.

Structural adjustments through training system choice, row orientation, and targeted canopy management can enhance LUE. Divided or high-wire systems, and single-curtain compared with pergola in humid climates, have been shown to increase light in the cluster zone, raise leaf photosynthetic rates in key canopy strata, and promote assimilate allocation to fruit. Opening dense canopies by shoot thinning or leaf removal increases porosity and fruit-zone light, often improving berry soluble solids and phenolic traits, although excessive exposure may risk flavonoid degradation in warm climates (Martínez-Lüscher et al., 2019; Torres et al., 2020). Functional-structural modeling further indicates that allowing non-uniform nitrogen and light distribution among leaves increases whole-canopy photosynthesis relative to uniform distributions, underscoring that canopy optimization should consider both geometry and physiological acclimation to heterogeneous light (Prieto et al., 2019).

Light distribution in grapevine canopies is highly heterogeneous, shaped by canopy density, geometry, and orientation. Dense canopies intercept large amounts of radiation but transmit little to the fruit zone and interior, whereas optimized architectures maintain adequate total interception while improving light penetration and use efficiency. Through informed selection of training systems and targeted canopy management, growers can refine light interception, enhance photosynthetic efficiency, and better support desirable fruit composition.

4 Effects of Canopy Structure on Grapevine Photosynthesis

4.1 Changes in leaf photosynthetic characteristics

Canopy structure alters the light and thermal environment around leaves, driving changes in net photosynthetic rate (Pn), stomatal conductance (Gs) and transpiration (Tr). Opening dense Cabernet Sauvignon canopies increased photon flux density and daily light integral, leading to higher photosynthetic rate and transpiration during vegetative growth (Hernández-Ordoñez et al., 2024). Under field shading, reduced PAR lowered Pn, transpiration and stomatal conductance, while light compensation and saturation points shifted downward, indicating acclimation to low light but with reduced radiation-saturated Pn.

Stomatal regulation links these structural and microclimatic shifts to water use. At the canopy scale, bulk stomatal conductance varies diurnally with vapor pressure deficit and net radiation, and declines seasonally as soil water deficits develop (Gowdy et al., 2022). Grapevine canopies can reduce conductance exponentially with increasing vapor pressure deficit to stabilize transpiration, maintaining near-constant water loss despite large atmospheric demand changes. Progressive drought reduces Pn and Tr first in sun-exposed leaves, and later across the canopy, with stomatal conductance emerging as a key integrative indicator of photosynthetic down-regulation in C3 plants including grapevine (Medrano et al., 2002; Escalona et al., 2020).

4.2 Differences in photosynthesis among leaves at different canopy layers

Light gradients created by canopy structure cause strong vertical differences in leaf gas exchange. In overhead parronal systems, the highest canopy photosynthesis comes from mid-layers (about 20-40 cm above the trellis), where leaves experience mixed shade and sunflecks; leaves at the very top show some photoinhibition, while lower leaves remain productive rather than parasitic (Cortázar et al., 2005). In vertically trellised Shiraz, photosynthetic output declines from apical to basal canopy zones, with particularly low and erratic values in the light-limited interior, reflecting strong light constraints in the centre of dense canopies (Hunter et al., 2020).

Drought and row orientation further modulate these layer differences. Under progressive water deficit, photosynthesis and transpiration are first reduced in outer sunlit leaves, with shaded inner leaves affected later and some deeply shaded leaves remaining almost unresponsive but with negligible carbon gain (Escalona et al., 2020). Orientation-driven radiation patterns lead to higher average Pn on east and north-facing sides, while south-exposed layers show lower photosynthesis and more negative water status. Functional-structural modelling confirms that differences in leaf nitrogen distribution and light interception among layers translate into substantial variation in their contribution to whole-canopy carbon gain under different training systems (Prieto et al., 2019).

4.3 Accumulation and transport of photosynthates

Changes in Pn, Gs and Tr at leaf and canopy levels ultimately determine the supply of photosynthates available for growth and fruit ripening. Defoliation experiments show that reductions in leaf area (source) have a stronger effect on season-long carbon assimilation, sugar-induced growth and speed of ripening than changes in crop load, underscoring the dominance of canopy size and activity over sink level (Martínez-Lüscher and Kurtural, 2021). Under shading, reduced Pn is accompanied by lower leaf soluble carbohydrates and starch, as well as decreased vine yield and berry soluble solids, indicating limited carbohydrate production and altered allocation.

Photosynthate transport depends on both whole-plant carbon balance and phloem capacity. Long-term shading experiments reveal that, despite depressed photosynthesis, shaded grapevine leaves can maintain non-structural carbohydrate pools due to reduced sink demand, but this accumulation constrains full photosynthetic recovery when leaves are re-exposed to sun (Gallo et al., 2024). Hormonal regulation by abscisic acid and gibberellin can shift carbon allocation by increasing non-structural carbohydrates in leaves, enlarging phloem area, and up-regulating sugar transporter genes in leaves and berries, thereby accelerating hexose accumulation in fruit or enhancing stem growth (Figure 2) (Murcia et al., 2016; Li et al., 2021).

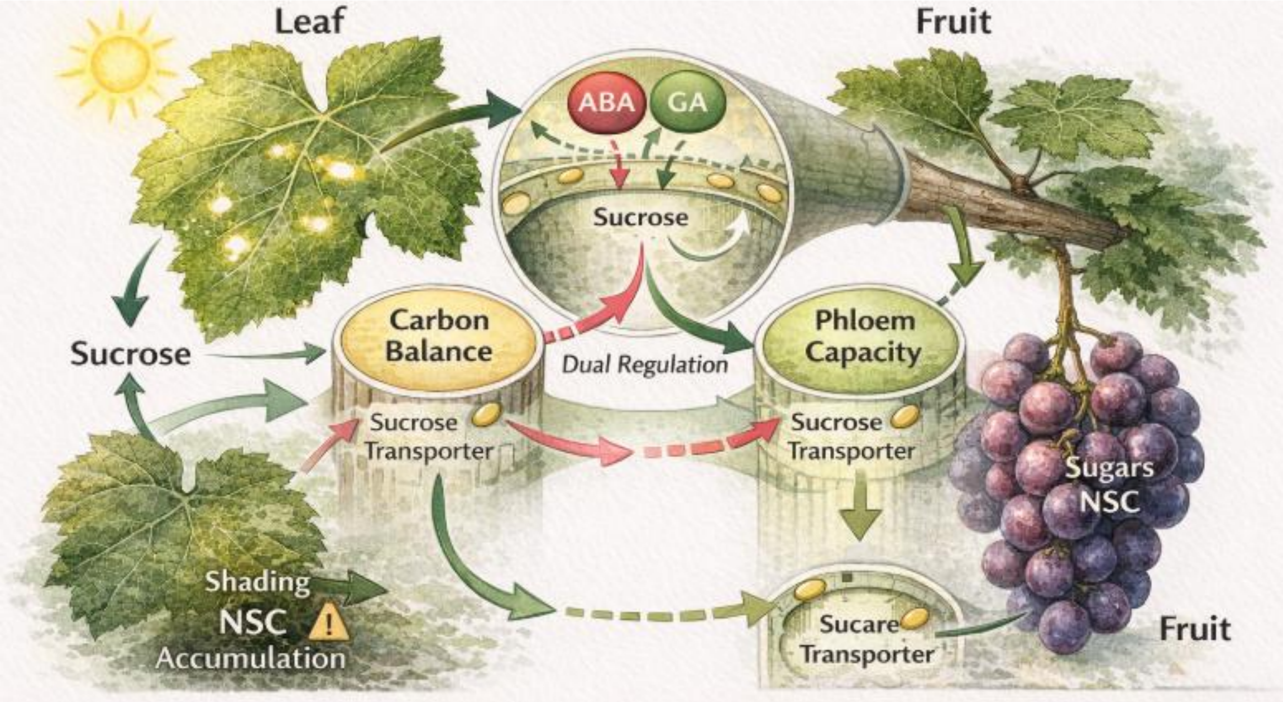

Figure 2 Mechanisms of photosynthate transport and hormonal regulation in grapevines, highlighting phloem function and carbohydrate allocation (Adopted from Li et al., 2021)

Canopy structure shapes Pn, Gs and Tr by modifying light and water status, with open, well-lit canopies generally enhancing photosynthesis but increasing transpirational demand. Strong vertical gradients in radiation and water potential create sharp differences in photosynthesis among canopy layers, so mid-canopy leaves in mixed light often dominate carbon gain. These physiological patterns control carbohydrate accumulation and transport, where adequate, well-distributed active leaf area and effective phloem function are critical for sustaining fruit sugar accumulation and overall vine performance.

5 Effects of Canopy Structure on Fruit Quality

5.1 Influence on sugar accumulation

Canopy structure, through its effects on source-sink balance and microclimate, strongly regulates the rate and extent of sugar accumulation in berries. Shoot thinning, which reduces crop load and increases canopy porosity, consistently hastened ripening and increased total soluble solids (TSS) by about 2.5 Brix in Cabernet Sauvignon, although it reduced yield (Torres et al., 2020). Similarly, early or cluster-zone leaf removal often increases berry sugar and final wine alcohol, indicating that greater light exposure and a higher leaf-to-fruit ratio can accelerate sugar accumulation when temperature is not excessive (Stefanović et al., 2021). These responses show that structural manipulations of the canopy can shift the trajectory of berry sugar dynamics.

Conversely, increasing shading within the canopy tends to slow sugar accumulation and delay maturity. Partial canopy shade that reduced solar radiation by ~75% lowered leaf net assimilation and resulted in berries with reduced TSS and delayed phenological development compared with unshaded vines (Lu et al., 2021). Artificial canopy shading applied at fruit set likewise decreased sugar concentration at harvest and increased must acidity, pointing to a general slowing of ripening under reduced light and temperature (Miccichè et al., 2023). Late-season canopy reduction by shoot trimming can also decrease final TSS without major changes in yield, providing a tool to moderate excessive sugar in warm climates (Assefa et al., 2025).

5.2 Regulation of organic acids and flavor compounds

Canopy structure alters berry temperature and light, thereby modifying organic acid degradation and acid-sugar balance. Shading treatments that reduce irradiance and berry temperature generally increase titratable acidity and lower pH at harvest, as shown for partially shaded Cabernet Sauvignon and shaded Nero d'Avola. In contrast, cluster-zone leaf removal typically lowers titratable acidity, even when TSS is unchanged, reflecting faster organic acid catabolism in warmer, better-exposed berries (Anić et al., 2021; Yao et al., 2024). These changes in acids interact with sugar levels to define harvest ripeness and wine freshness.

Flavor and aroma compounds are also highly sensitive to canopy-driven microclimate. Increased exposure from shoot thinning and leaf removal decreased methoxypyrazines (green, herbaceous notes) in warm-climate Cabernet Sauvignon, improving sensory maturity despite only modest flavonoid gains (Torres et al., 2020). In semi-arid conditions, partial canopy shading enhanced fruity and floral wine aroma by increasing esters and β-damascenone, while also altering C6/C9 and fatty acid precursors in berries. Full cluster shading from veraison to harvest changed volatile profiles in Cabernet Sauvignon, with higher total volatiles and shifts toward fruity, herbaceous, floral, and mushroom notes compared with exposed clusters (Liu et al., 2024).

5.3 Effects on color and secondary metabolites

The relationship between canopy structure and berry color is complex, as light and temperature can both stimulate and degrade pigments. In warm climates, increased cluster exposure via leaf removal or shoot thinning hastened maturity but did not consistently raise total anthocyanins at harvest, and flavonols were the only group clearly upregulated with higher solar radiation (Torres et al., 2020). Excessive exposure crossed degradation thresholds for some flavonoids, indicating that there is an optimal range of radiation for color development beyond which anthocyanins and other compounds decline. By contrast, early leaf removal in Eastern Serbia increased anthocyanins and total phenolics in Cabernet Sauvignon skins and wines, particularly under temperate warm conditions where overexposure risk was lower (Stefanović et al., 2021).

Moderate shading can also enhance or preserve color and phenolic quality under very hot, high-radiation conditions. Partial canopy shade increased berry and wine anthocyanin concentrations in a semi-arid site, while reducing flavonols, suggesting that lower temperatures favored anthocyanin stability despite reduced light. Full cluster shading from veraison decreased anthocyanins, phenols, and tannins, showing that excessive shade can suppress phenolic synthesis when light becomes limiting (Liu et al., 2024). Cluster-zone leaf removal at different stages often increases berry anthocyanins and flavonols across cultivars and seasons, though it may reduce certain aroma-related norisoprenoids, emphasizing trade-offs between color and specific flavor precursors (Yao et al., 2024).

Across these studies, canopy structure modulates sugar accumulation, acid metabolism, aroma formation, and phenolic composition by reshaping light and temperature around clusters. Practices that open the canopy tend to increase TSS, lower acidity, and adjust volatile and phenolic profiles toward riper styles, while shading slows sugar accumulation, preserves acids, and can either enhance or depress color depending on climate severity. Effective canopy design therefore requires cultivar- and climate-specific balancing of exposure to optimize soluble solids, flavor, and secondary metabolites simultaneously.

6 Canopy Management Practices and Their Regulatory Effects

6.1 Effects of pruning methods

Winter pruning primarily regulates bud number, potential crop load, and the renewal zone light environment that determines bud fruitfulness for the next season. Lighter winter pruning with more buds retained can increase shoot number but may reduce individual shoot vigor and modify bud microclimate (Collins et al., 2020). Delayed winter pruning, performed when apical shoots already bear unfolded leaves, can postpone budburst by 15-30 days and partially shift ripening into cooler periods without large yield penalties (Gatti et al., 2016). Such late pruning also altered seasonal canopy phenology and increased cumulative carbon gain per vine through higher and more sustained canopy net CO_2 exchange.

Double pruning and very late winter pruning have been proposed as tools to adapt to both excessive summer heat and spring frost risk. In Brazilian ‘Syrah’, a double-pruning strategy that induced a winter harvest improved sugar and phenolic accumulation and reduced rot incidence compared with the traditional summer harvest (Favero et al., 2020). A review on frost mitigation shows that two-step delayed winter pruning exploits acrotony to “sacrifice” apical shoots to frost while preserving basal buds, thereby reducing damage and sometimes delaying maturity into a cooler window (Poni et al., 2022). These approaches modify canopy structure and functioning over the whole cycle, with cascading effects on photosynthesis and berry quality.

6.2 Leaf removal and shoot thinning techniques

Leaf removal and shoot thinning are key summer pruning operations used to adjust canopy density, fruit exposure, and the source–sink balance. Pre-bloom leaf removal and shoot trimming, applied at different positions along the shoot, differentially altered fruit set, berry number per bunch, berry weight, and composition by modifying local source leaves and assimilate supply (Mataffo et al., 2023). Basal defoliation at fruit set in Cabernet Sauvignon increased single-leaf photosynthesis, changed berry temperature profiles, and shifted soluble solids, titratable acidity, and phenolic composition, with moderate defoliation often favoring higher Brix and extractable anthocyanins (Figure 3) (Cataldo et al., 2021).

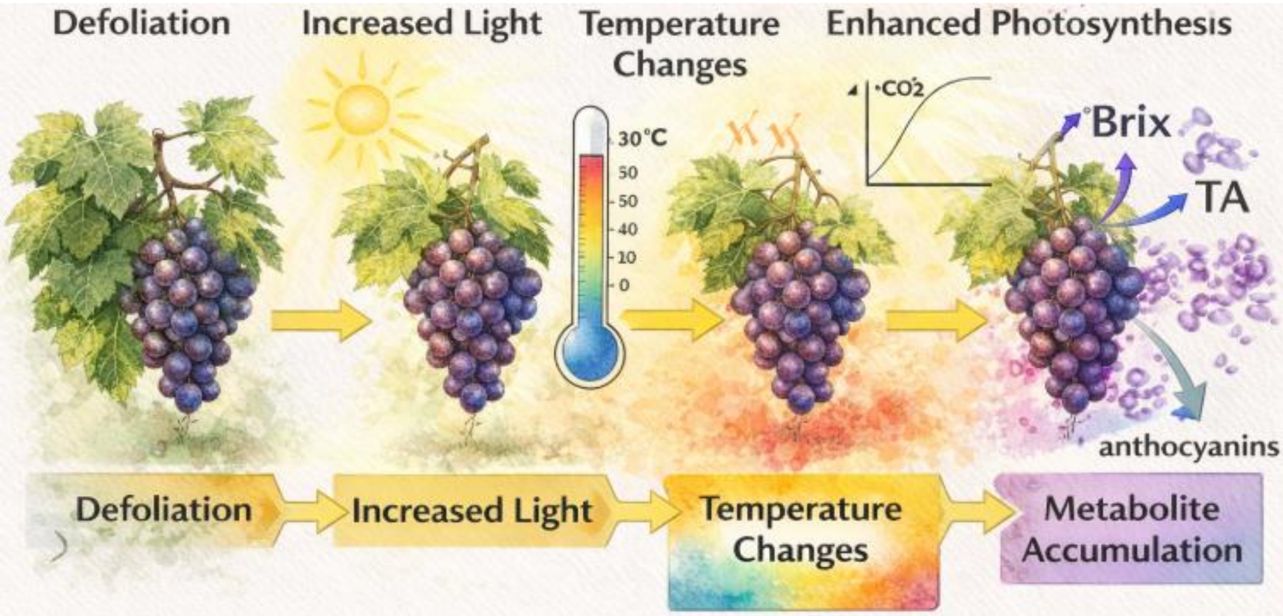

Figure 3 Effects of basal defoliation on fruit-zone microclimate and berry composition, including changes in temperature, photosynthesis, and metabolite accumulation (Adopted from Cataldo et al., 2021)

Shoot thinning and its combination with defoliation can open the fruiting zone and reduce leaf layer number, but their effects on yield and composition are not uniform across climates and seasons. In Montepulciano, shoot thinning alone reduced canopy density but did not consistently reduce yield or improve fruit composition, whereas shoot thinning combined with pre-flowering defoliation decreased yield, reduced Botrytis incidence, and improved berry composition, with carry-over effects on yield the following year (Silvestroni et al., 2018). A broader study showed that leaf removal and shoot thinning modify bud light interception and carbohydrate status, thereby influencing bud fruitfulness and inflorescence primordia size, which link current-season canopy management to future yield potential (Collins et al., 2020).

6.3 Training systems and shoot positioning

Training systems and shoot positioning define canopy geometry, affecting total leaf area, exposed leaf area, and the proportion of sunlit versus shaded leaves. A comprehensive review highlights that divided canopy systems and alternatives to classical VSP can simultaneously increase yield and improve fruit composition by optimizing the light microclimate of leaves and clusters (Reynolds and Heuvel, 2009). Recent whole-canopy gas-exchange work comparing VSP, single high wire, and pergola structures in Sangiovese showed that, per unit leaf area, single high wire canopies achieved higher net CO_2 exchange and better drought resilience, whereas pergola attained superior fruit maturity at similar yields (Del Zozzo et al., 2024).

Shoot orientation and trellis form interact strongly with cultivar architecture to determine light interception and fruit exposure. Three-dimensional modeling of VSP versus non-positioned systems (gobelet and bilateral free cordon) demonstrated that free-standing canopies can have higher light interception and a greater proportion of sunlit leaf area at intermediate LAI, particularly benefiting cultivars with procumbent shoots (Louarn et al., 2008). In a humid Chinese region, a single-curtain system increased cluster-zone PPFD, improved leaf chlorophyll content and mid-shoot photosynthetic capacity, and enhanced assimilate allocation to fruit compared with a pergola system, resulting in higher soluble solids and more favorable vegetative–reproductive balance (Du et al., 2023). Thoughtful choice of training and shoot positioning thus provides a structural framework within which pruning, leaf removal, and thinning can fine-tune canopy function and fruit quality.

7 Interactive Effects of Environmental Factors and Canopy Structure

7.1 Influence of light intensity and climatic conditions

Light intensity and thermal regime interact with canopy structure to shape photosynthesis and berry composition. Row orientation modifies the angle and timing of solar radiation on canopy walls, creating distinct patterns of leaf water potential and photosynthetic activity among orientations and canopy sides (Hunter et al., 2020). In Shiraz, canopies oriented north-south or east-west showed the highest average photosynthesis, while south- and southwest-facing sides had lower photosynthetic output under less favorable radiation and temperature conditions. At the berry level, different orientations and exposure patterns generate contrasting pulp temperatures, which in turn drive differences in sugar ripening and skin phenolics (Hunter et al., 2021).

Climate warming increases the risk of radiative excess and high berry temperatures, which can accelerate sugar ripening but compromise acid balance and color stability (Miccichè et al., 2023). In warm regions, porous or divided canopies that temper afternoon heat loads can support better phenolic accumulation than highly exposed VSP walls, especially when combined with adjusted row orientation (Reynolds and Heuvel, 2009). Shading nets applied at fruit set reduced berry temperature, delayed phenology, increased must acidity and decreased pH, illustrating how reduced light and moderated heat can slow ripening and modify grape composition under hot conditions. Such findings highlight the need to match canopy openness and exposure with local radiation and temperature regimes.

7.2 Regulation of canopy structure by water and nutrient supply

Water availability strongly regulates canopy size, density, and thus microclimate. In potted Sangiovese, reduced irrigation to 50%-35% of full supply decreased net CO_2 exchange and transpiration, especially in VSP and pergola geometries, while single high-wire canopies maintained higher photosynthetic efficiency and drought resilience (Figure 4) (Del Zozzo et al., 2024). Field trials combining six trellis systems with three irrigation levels showed that higher applied water increased leaf area, berry size, and yield, whereas low water (25% ET replacement) limited vegetative growth but enhanced berry anthocyanin and flavonol concentrations (Yu et al., 2022). These responses indicate that irrigation regimes co-define canopy architecture and its functional quality in warm climates.

Nutrient status, particularly nitrogen, interacts with water to control vigor and canopy development. Reviews of deficit irrigation and vine mineral nutrition emphasize that limited water combined with moderate nitrogen can reduce canopy size, berry size, and disease incidence, while accelerating ripening and improving color (Keller, 2005). Growth is more sensitive than photosynthesis to both water and nitrogen shortage, so controlled deficits can restrain excessive canopy expansion and prevent overly dense, shaded canopies. However, severe water or nitrogen limitation may reduce assimilate supply and lead to excessive fruit exposure, suggesting that water-nutrient management must be finely tuned to sustain a functional canopy structure.

7.3 Adaptability of canopy structures in different ecological regions

The suitability of canopy systems differs among ecological regions, depending on temperature, radiation, and water availability. In Californian warm climates, single high-wire and high-quadrilateral trellises achieved greater yields and higher berry anthocyanin derivatives than conventional VSP, while increased crown porosity in VSP raised flavonol levels but was associated with lower photosynthetic capacity and translocation efficiency (Yu et al., 2022). In Brazilian tropical conditions, VSP training provided higher vine water status but lower berry Brix compared with a modified Geneva Double Curtain, illustrating a trade-off between water relations and fruit exposure in a hot, seasonally dry region (Favero et al., 2010). Reviews of training systems under climate change propose re-evaluating divided and high-wire systems, particularly in warm and sub-tropical zones where VSP often requires intensive manipulation to avoid overexposure and rapid ripening (Del Zozzo and Poni, 2024).

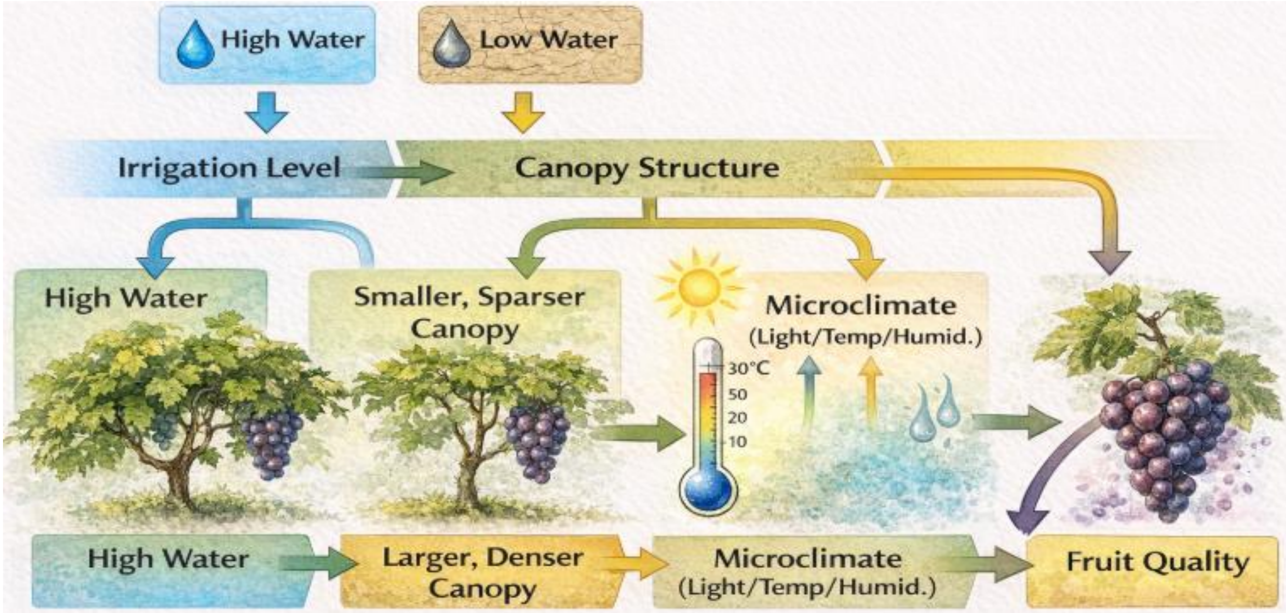

Figure 4 Conceptual model illustrating how water availability regulates canopy structure, microclimate, and physiological processes affecting grapevine performance (Adopted from Del Zozzo et al., 2024)

In humid, rainy regions, canopy structures must also address disease pressure and excess vigor. For the 'Miguang' grape in a rainy Chinese region, a single-curtain system improved cluster-zone light, leaf photosynthetic capacity, and assimilate distribution to fruit compared with a pergola, while simultaneously decreasing vegetative growth (Du et al., 2023). Systematic reviews of climate-change adaptation highlight that combining location, training system, irrigation, and canopy management at multiple scales allows region-specific compromises between water use and productivity (Naulleau et al., 2021). Across cool, temperate, and warm areas, training choices therefore need to integrate local climate, water resources, and disease risk to select canopy architectures that maintain photosynthetic efficiency and fruit quality under changing environments.

8 Case Study: Effects of Typical Canopy Management Systems on Grape Quality

8.1 Comparison of photosynthetic efficiency under different training systems

Training system geometry shapes how efficiently grape canopies convert intercepted light into carbon gain. In potted Sangiovese, whole-canopy gas exchange showed that, when expressed per unit leaf area, the single high wire (SHW) system achieved about 24% higher net CO_2 exchange than both VSP and pergola under well-watered conditions, highlighting superior photosynthetic efficiency of more elevated, sprawling canopies (Del Zozzo et al., 2024). Under progressive water deficit, SHW maintained higher NCER/leaf area and transpiration/leaf area, while VSP and pergola exhibited stronger declines in light saturation point and quantum yield, indicating lower drought resilience and efficiency.

Training systems also differ in how they reconcile photosynthetic efficiency with fruit ripening and composition. Despite lower NCER/leaf area than SHW, the pergola system reached the best fruit maturity at comparable yields, suggesting a favorable balance between light interception, evaporative cooling, and source–sink relations. A broader review confirms that divided or non-VSP systems (e.g., pergola, high wires, GDC) can improve overall efficiency by enhancing light distribution and balancing dry-matter partitioning, while conventional VSP often achieves good control of vigor but may require multiple canopy operations to maintain internal light and avoid excessive berry heating in warm climates (Del Zozzo and Poni, 2024).

8.2 Empirical analysis of moderate leaf removal on fruit quality improvement

Moderate basal leaf removal is widely used to alter cluster microclimate without excessively reducing source capacity. In Cabernet Sauvignon, removal of four basal leaves at fruit set (LR4) increased single-leaf photosynthesis and resulted in grapes with higher Brix and greater extractable anthocyanins and polyphenols compared with the untreated control, showing that a modest reduction in leaf area can enhance both technological and phenolic ripeness (Cataldo et al., 2021). A more severe treatment (removal of eight leaves) increased titratable acidity and did not further improve color compounds, indicating that beyond a certain threshold defoliation may cool clusters and slow sugar and phenolic accumulation.

Regional trials in continental Croatia likewise demonstrated quality gains from moderate cluster-zone defoliation in Merlot. Basal leaf and lateral removal at berry set increased UV radiation in the fruiting zone, which did not change sugar concentration but significantly reduced titratable acidity and enhanced skin phenols, anthocyanins, flavonols, and flavan-3-ols, particularly in the cooler ripening season (Anić et al., 2021). A multiyear transcriptomic analysis of pre-flowering defoliation further showed consistent up-regulation of genes involved in flavonoid biosynthesis and hormonal signaling across sites and cultivars, supporting the robustness of early leaf removal in improving composition when carefully calibrated to climate and vigor (Zenoni et al., 2017).

8.3 Successful regional practices of canopy optimization

Successful canopy optimization strategies are strongly region- and climate-specific, combining training choice with targeted summer operations. In rainy eastern China, a single-curtain (SCT) system outperformed a pergola for ‘Miguang’ by increasing photosynthetic photon flux density in the cluster zone, enhancing chlorophyll and leaf area of mid-shoot leaves, and promoting assimilate allocation to fruit, which translated into higher berry soluble solids and lower titratable acidity under humid, low-light conditions (Du et al., 2023). In cold semiarid Ukraine, free-growing shoots on a 1.2-m cordon created a canopy with optimal leaf index and relatively low transpiration, improving photosynthetic apparatus activity and yield stability in dry years, thus enabling non-irrigated production (Shtirbu et al., 2022).

In warm and hot regions, canopy modifications increasingly aim to buffer heat and radiation while maintaining efficient photosynthesis. Leaning VSP canopies 30° toward the west in a temperate-warm Spanish site increased morning radiation on Bobal vines and reduced afternoon heating, resulting in musts and wines with higher acidity, lower pH, and greater color intensity, anthocyanins, polyphenols, and aroma esters than standard VSP (Ferrer-Gallego et al., 2024). Systematic reviews of adaptation strategies underline that combining such architectural changes with irrigation and other levers at multiple scales offers the most promising path to maintain productivity and quality under climate change while respecting local constraints and grower capacity (Naulleau et al., 2021).

9 Conclusions and Future Perspectives

Research on canopy structure in grapevines shows that training system, geometry and density jointly determine light interception, whole-canopy gas exchange and, ultimately, fruit composition. Systems such as single high wire, high quadrilateral or pergola can achieve higher whole-canopy net CO_2 exchange per unit leaf area and better drought resilience than traditional VSP, while still reaching good fruit maturity in warm climates. Across systems, the best predictor of photosynthesis is the amount and timing of direct light intercepted by the canopy, whereas transpiration is tightly related to vapor pressure deficit, highlighting the central role of canopy architecture in mediating climate effects. Canopy manipulation techniques including defoliation, shading nets, and early canopy management at pre-bloom further refine this structural control over microclimate and source–sink balance. Basal defoliation at fruit set can increase single-leaf photosynthesis, adjust berry temperature, and improve soluble solids and anthocyanin extractability when severity is moderate. Shading nets and altered training height or leaning reduce berry temperature and slow ripening, often preserving acidity and preventing flavonoid degradation under hot conditions. Early leaf removal or shoot trimming at specific positions along the shoot modulates fruit set, bunch compactness and berry composition, showing that both the amount and spatial distribution of leaf area are critical for balancing yield and fruit quality.

Despite extensive work, several limitations constrain the current understanding and application of canopy-based strategies. Many studies evaluate single levers (e.g., training system alone or a specific defoliation regime) under narrow climatic and cultivar conditions, making it difficult to generalize results or predict performance under future climates. Systematic reviews emphasize that most adaptation studies lack multi-lever and multi-scale approaches, and rarely quantify economic feasibility, restricting their usefulness for decision-makers in commercial vineyards. There is also incomplete coverage of the diversity of canopy forms and their long-term physiological impacts. Reviews indicate that classical systems such as VSP and goblet, though widely used, may be less aligned with future climate demands, yet empirical comparisons with alternative systems in different regions remain limited. Evaluations often focus on a few compositional traits (sugars, basic phenolics) and short time frames, while long-term effects on carbohydrate reserves, vine longevity, and cumulative yield are less frequently addressed. These gaps hinder precise recommendations on optimal canopy structures across ecologically contrasting regions.

Future research needs to integrate canopy architecture with other adaptation levers, especially under projected climate scenarios. Systematic assessments show that combining changes in training system, irrigation regime, soil and floor management, and canopy manipulation leads to more robust adaptation strategies than any single intervention alone. Modelling tools that couple gas exchange, water status, leaf temperature and radiation load can be expanded to simulate how alternative trellis designs, shading devices and reflective treatments interact with heatwaves and water scarcity. Such approaches could guide site-specific canopy designs that maintain photosynthesis while protecting fruit quality. At the application level, regionally tailored canopy systems offer promising prospects. Reviews of training systems under warming suggest re-evaluating high-wire, divided and non-VSP canopies in warm and semi-arid areas, while using more exposing systems in newly suitable cool regions to accelerate ripening. Recent work also points to using berry skin flavonols as practical indicators of canopy architecture and radiation exposure, supporting precision management of leaf area and porosity in the field. Coupling these physiological indicators with remote sensing and decision tools could enable dynamic canopy management that sustains photosynthetic efficiency and fruit quality across increasingly variable ecological conditions.

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The author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

References
Abubakar M., Chanzy A., Flamain F., and Courault D., 2023, Characterisation of grapevine canopy leaf area and inter-row management using Sentinel-2 time series, OENO One, 57(4): 7703.
https://doi.org/10.20870/oeno-one.2023.57.4.7703

Anić M., Osrečak M., Andabaka Ž., Tomaz I., Večenaj Ž., Jelić D., Kozina B., Kontić J.K., and Karoglan M., 2021, The effect of leaf removal on canopy microclimate, vine performance and grape phenolic composition of Merlot (*Vitis vinifera* L.) grapes in the continental part of Croatia, Scientia Horticulturae, 285: 110161.
https://doi.org/10.1016/j.scienta.2021.110161

Assefa M., Creasy G., Hofmann R., and Parker A., 2025, Asynchronous accumulation of sugar and phenolics in grapevines following post-veraison leaf removal, OENO One, 59(2): 9314.
https://doi.org/10.20870/oeno-one.2025.59.2.9314

Cataldo E., Salvi L., Paoli F., Fucile M., and Mattii G.B., 2021, Effects of defoliation at fruit set on vine physiology and berry composition in Cabernet Sauvignon grapevines, Plants, 10(6): 1183.
https://doi.org/10.3390/plants10061183

Collins C., Wang X., Lesefko S., Bei R., and Fuentes S., 2020, Effects of canopy management practices on grapevine bud fruitfulness, OENO One, 54(2): 313-325.
https://doi.org/10.20870/oeno-one.2020.54.2.3016

Comba L., Biglia A., Aimonino D.R., Tortia C., Mania E., Guidoni S., and Gay P., 2020, Leaf Area Index evaluation in vineyards using 3D point clouds from UAV imagery, Precision Agriculture, 21: 881-896.
https://doi.org/10.1007/s11119-019-09699-x

Cortázar V., Cordova C., and Pinto M., 2005, Canopy structure and photosynthesis modelling of grapevines (*Vitis vinifera* L. cv. Sultana) grown on an overhead (parronal) trellis system in Chile, Australian Journal of Grape and Wine Research, 11(3): 328-338.
https://doi.org/10.1111/j.1755-0238.2005.tb00032.x

Del Zozzo F., and Poni S., 2024, Climate Change Affects Choice and Management of Training Systems in the Grapevine, Australian Journal of Grape and Wine Research, 2024: 7834357.
https://doi.org/10.1155/2024/7834357

Del Zozzo F., Magnanini E., and Poni S., 2024, Physiological efficiency of grapevine canopies having varying geometries: seasonal and diurnal whole canopy gas exchange assessment under well-watered and water deficit conditions, Environmental and Experimental Botany, 224: 105716.
https://doi.org/10.1016/j.envexpbot.2024.105716

Du W., Li S., Du T., Huang W., Zhang Y., Kang H., Yao Y., Gao Z., and Du Y., 2023, 'Miguang' grape response to pergola and single-curtain training systems, Horticulturae, 9(1): 113.
https://doi.org/10.3390/horticulturae9010113

Escalona J.M., Flexas J., Bota J., and Medrano H., 2003, Distribution of leaf photosynthesis and transpiration within grapevine canopies under different drought conditions, Vitis, 42(2): 57-64.
https://doi.org/10.5073/vitis.2003.42.57-64

Favero A.C., Amorim D.A., Mota R.V., Soares Â.M., Souza C.R., and Regina M.A., 2011, Double-pruning of "Syrah" grapevines: a management strategy to harvest wine grapes during the winter in the Brazilian Southeast, Vitis, 50(4): 151-158.

Favero A.C., Amorim D.A., Mota R.V., Souza C.R., and Regina M.A., 2010, Physiological responses and production of 'Syrah' vines as a function of training systems, Scientia Agricola, 67(3): 267-273.
https://doi.org/10.1590/s0103-90162010000300003

Ferrer-Gallego R., Buesa I., García-Esparza M.J., Alvarez I., Intrigliolo D.S., Ramírez-Cuesta J.M., and Lizama V., 2024, Effects of grapevine canopy leaning on grape composition and wine quality of 'Bobal', OENO One, 58(3): 8014.
https://doi.org/10.20870/oeno-one.2024.58.3.8014

Gallo A., Christophe A., Poupard M., Boulord R., Rolland G., Prieto J.A., Simonneau T., and Pallas B., 2024, Effects of acclimation to long-term shading on photosynthesis in grapevines: roles of non-structural carbohydrates and stomatal conductance, Physiologia Plantarum, 176(6): e14636.
https://doi.org/10.1111/ppl.14636

Gatti M., Pirez F.J., Chiari G., Tombesi S., Palliotti A., Merli M.C., and Poni S., 2016, Phenology, canopy aging and seasonal carbon balance as related to delayed winter pruning of *Vitis vinifera* L. cv. Sangiovese grapevines, Frontiers in Plant Science, 7: 659.
https://doi.org/10.3389/fpls.2016.00659

Gladstone E.A., and Dokoozlian N.K., 2003, Influence of leaf area density and trellis/training system on the light microclimate within grapevine canopies, Vitis, 42(3): 123-131.
https://doi.org/10.5073/vitis.2003.42.123-131

Gowdy M., Pieri P., Suter B., Marguerit E., Destrac-Irvine A., Gambetta G.A., and van Leeuwen C., 2022, Estimating bulk stomatal conductance in grapevine canopies, Frontiers in Plant Science, 13: 839378.
https://doi.org/10.3389/fpls.2022.839378

Hernández-Ordoñez E., Cruz-Álvarez O., Orozco-Avitia J., Hernández-Rodríguez O.A., Alonso-Villegas R., Jacobo-Cuéllar J.L., Gardea-Bejar A.A., and Ojeda-Barrios D.L., 2024, Physiological responses of Cabernet Sauvignon to dividing canopies in the Chihuahuan Desert, Agriculture, 14(12): 2101.
https://doi.org/10.3390/agriculture14122101

Hunter J.J., Tarricone L., Volschenk C.G., Giacalone C., Melo M.S., and Zorer R., 2020, Grapevine physiological response to row orientation-induced spatial radiation and microclimate changes, OENO One, 54(2): 411-433.
https://doi.org/10.20870/oeno-one.2020.54.2.3100

Hunter J.J., Volschenk C.G., Mania E., Castro A., Booyse M., Guidoni S., Pisciotta A., Di Lorenzo R., Novello V., and Zorer R., 2021, Grapevine row orientation mediated temporal and cumulative microclimatic effects on grape berry temperature and composition, Agricultural and Forest Meteorology, 310: 108660.
https://doi.org/10.1016/j.agrformet.2021.108660

Iandolino A.B., Pearcy R.W., and Williams L.E., 2013, Simulating three-dimensional grapevine canopies and modelling their light interception characteristics, Australian Journal of Grape and Wine Research, 19(3): 388-400.
https://doi.org/10.1111/ajgw.12036

Keller M., 2005, Deficit irrigation and vine mineral nutrition, American Journal of Enology and Viticulture, 56(3): 267-283.
https://doi.org/10.5344/ajev.2005.56.3.267

Li Y., Forney C.F., Bondada B., Leng F., and Xie Z., 2021, The molecular regulation of carbon sink strength in grapevine (*Vitis vinifera* L.), Frontiers in Plant Science, 11: 606918.
https://doi.org/10.3389/fpls.2020.606918

Liu M., Ji H., Jiang Q., Liu T., Cao H., and Zhang Z., 2024, Effects of full shading of clusters from véraison to ripeness on fruit quality and volatile compounds in Cabernet Sauvignon grapes, Food Chemistry: X, 21: 101232.
https://doi.org/10.1016/j.fochx.2024.101232

Louarn G., Dauzat J., Lecoeur J., and Lebon É., 2008, Influence of trellis system and shoot positioning on light interception and distribution in two grapevine cultivars with different architectures: an original approach based on 3D canopy modelling, Australian Journal of Grape and Wine Research, 14(2): 143-152.
https://doi.org/10.1111/j.1755-0238.2008.00016.x

Louarn G., Lecoeur J., and Lebon É., 2008, A three-dimensional statistical reconstruction model of grapevine (*Vitis vinifera*) simulating canopy structure variability within and between cultivar/training system pairs, Annals of Botany, 101(8): 1167-1184.
https://doi.org/10.1093/aob/mcm170

Lu H., Wei W., Wang Y., Duan C., Chen W., Li S., and Wang J., 2021, Effects of sunlight exclusion on leaf gas exchange, berry composition, and wine flavour profile of Cabernet-Sauvignon from the foot of the north side of Mount Tianshan and a semi-arid continental climate, OENO One, 55(2): 267-283.
https://doi.org/10.20870/oeno-one.2021.55.2.4545

Mabrouk H., Carbonneau A., and Sinoquet H., 1997, Canopy structure and radiation regime in grapevine. 1. Spatial and angular distribution of leaf area in two canopy systems, Vitis, 36(3): 119-123.

Martínez-Lüscher J., and Kurtural S.K., 2021, Same season and carry-over effects of source-sink adjustments on grapevine yields and non-structural carbohydrates, Frontiers in Plant Science, 12: 695319.
https://doi.org/10.3389/fpls.2021.695319

Martínez-Lüscher J., Brillante L., and Kurtural S.K., 2019, Flavonol profile is a reliable indicator to assess canopy architecture and the exposure of red wine grapes to solar radiation, Frontiers in Plant Science, 10: 10.
https://doi.org/10.3389/fpls.2019.00010

Mataffo A., Scognamiglio P., Molinaro C., Corrado G., and Basile B., 2023, Early canopy management practices differentially modulate fruit set, fruit yield, and berry composition at harvest depending on the grapevine cultivar, Plants, 12(4): 733.
https://doi.org/10.3390/plants12040733

Medrano H., Escalona J.M., Bota J., Gulías J., and Flexas J., 2002, Regulation of photosynthesis of C3 plants in response to progressive drought: stomatal conductance as a reference parameter, Annals of Botany, 89(Special Issue): 895-905.
https://doi.org/10.1093/aob/mcf079

Miccichè D., De Rosas M., Ferro M., Di Lorenzo R., Puccio S., and Pisciotta A., 2023, Effects of artificial canopy shading on vegetative growth and ripening processes of cv. Nero d'Avola (*Vitis vinifera* L.), Frontiers in Plant Science, 14: 1210574.
https://doi.org/10.3389/fpls.2023.1210574

Murcia G., Pontin M., Reinoso H., Baraldi R., Bertazza G., Gomez-Talquenca S., Bottini R., and Piccoli P., 2016, ABA and GA3 increase carbon allocation in different organs of grapevine plants by inducing accumulation of non-structural carbohydrates in leaves, enhancement of phloem area and expression of sugar transporters, Physiologia Plantarum, 156(3): 323-337.
https://doi.org/10.1111/ppl.12390

Naulleau A., Gary C., Prévot L., and Hossard L., 2021, Evaluating strategies for adaptation to climate change in grapevine production – a systematic review, Frontiers in Plant Science, 11: 607859.
https://doi.org/10.3389/fpls.2020.607859

Pallotti L., Partida G., Laroche-Pinel E., Lanari V., Pedroza M.A., and Brillante L., 2025, Late-season source limitation practices to cope with climate change: delaying ripening and improving colour of Cabernet-Sauvignon grapes and wine in a hot and arid climate, OENO One, 59(1): 8232.
https://doi.org/10.20870/oeno-one.2025.59.1.8232

Poni S., Sabbatini P., and Palliotti A., 2022, Facing spring frost damage in grapevine: recent developments and the role of delayed winter pruning – a review, American Journal of Enology and Viticulture, 73(3): 210-225.
https://doi.org/10.5344/ajev.2022.22011

Prieto J.A., Louarn G., Peña J.P., Ojeda H., Simonneau T., and Lebon É., 2020, A functional-structural plant model that simulates whole-canopy gas-exchange of grapevine plants (*Vitis vinifera* L.) under different training systems, Annals of Botany, 125(5): 833-848.
https://doi.org/10.1093/aob/mcz203

Reynolds A.G., and Vanden Heuvel J.E., 2009, Influence of grapevine training systems on vine growth and fruit composition: a review, American Journal of Enology and Viticulture, 60(3): 251-268.
https://doi.org/10.5344/ajev.2009.60.3.251

Shtirbu A., Kovaleva I., and Vlasov V., 2022, Responses of grapevines to planting density and training systems in semiarid environments, Agricultural Science and Practice, 9(2): 38-45.
https://doi.org/10.15407/agrisp9.02.038

Silvestroni O., Lanari V., Lattanzi T., Palliotti A., VanderWeide J., and Sabbatini P., 2018, Canopy management strategies to control yield and grape composition of Montepulciano grapevines, Australian Journal of Grape and Wine Research, 24(3): 321-330.
https://doi.org/10.1111/ajgw.12367

Stefanović D., Nikolic N., Kostić L., Todic S., and Nikolić M., 2021, Early leaf removal increases berry and wine phenolics in Cabernet Sauvignon grown in Eastern Serbia, Agronomy, 11(2): 238.
https://doi.org/10.3390/agronomy11020238

Torres N., Martínez-Lüscher J., Porte E., and Kurtural S.K., 2020, Optimal ranges and thresholds of grape berry solar radiation for flavonoid biosynthesis in warm climates, Frontiers in Plant Science, 11: 931.
https://doi.org/10.3389/fpls.2020.00931

Wang L., Brouard E., Prodhomme D., Hilbert G., Renaud C., Petit J., Edwards E., Betts A., Delrot S., Ollat N., Guillaumie S., Dai Z., and Gomès E., 2022, Regulation of anthocyanin and sugar accumulation in grape berry through carbon limitation and exogenous ABA application, Food Research International, 160: 111478.
https://doi.org/10.1016/j.foodres.2022.111478

Yao X., Wu Y., Lan Y., Cui Y., Shi T., Duan C., and Pan Q., 2024, Effect of cluster-zone leaf removal at different stages on Cabernet Sauvignon and Marselan (*Vitis vinifera* L.) grape phenolic and volatile profiles, Plants, 13(11): 1543.
https://doi.org/10.3390/plants13111543

Yu R., Torres N., Tanner J., Kacur S., Marigliano L., Zumkeller M., Gilmer J., Gambetta G.A., and Kurtural S.K., 2022, Adapting wine grape production to climate change through canopy architecture manipulation and irrigation in warm climates, Frontiers in Plant Science, 13: 1015574.
https://doi.org/10.3389/fpls.2022.1015574

Zenoni S., Dal Santo S., Tornielli G.B., D'Incà E., Filippetti I., Pastore C., Allegro G., Silvestroni O., Lanari V., Pisciotta A., Di Lorenzo R., Palliotti A., Tombesi S., Gatti M., and Poni S., 2017, Transcriptional responses to pre-flowering leaf defoliation in grapevine berry from different growing sites, years, and genotypes, Frontiers in Plant Science, 8: 630.
https://doi.org/10.3389/fpls.2017.00630

Zhu J., Parker A.K., Gou F., Agnew R., Yang L., Greven M., Raw V., Neal S., Martin D., Trought M.C.T., Huth N.I., and Brown H.E., 2021, Developing perennial fruit crop models in APSIM Next Generation using grapevine as an example, in silico Plants, 3(1): diab021.
https://doi.org/10.1093/insilicoplants/diab021

Feature Review Open Access

Effects of Biofertilizers on Soil Biological Activity in Vegetable Production Systems

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Abstract As a green agricultural input, biofertilizer plays a pivotal role in fostering soil health and promoting sustainable vegetable production. This paper systematically reviews the various types of biofertilizers and their underlying mechanisms of action, with a particular focus on their impact on soil biological activity within vegetable production systems. Investigations into key indicators-such as soil microbial community structure, enzyme activity, and soil respiration-reveal that biofertilizers can significantly enhance soil microbial diversity, boost the activity of critical enzymes, and facilitate nutrient cycling and transformation, thereby improving the soil ecological environment. Furthermore, by optimizing the rhizosphere micro-environment, biofertilizers indirectly contribute to improvements in both vegetable yield and quality. Through the analysis of representative case studies, the practical efficacy and potential of biofertilizers in actual production settings are further validated. Finally, this paper identifies current research gaps and outlines future directions for development, providing a theoretical foundation for the broader adoption and application of biofertilizers in vegetable production.

Keywords Biofertilizer; Soil biological activity; Vegetable production system; Microbial community; Soil enzyme activity

1 Introduction

Vegetable production systems are among the most input-intensive components of global agriculture, characterized by short rotations, high fertilizer application rates and frequent soil disturbance to achieve high yields and quality demanded by expanding populations and changing diets (Mahmud et al., 2021). Reliance on synthetic fertilizers has certainly contributed to yield gains, but it has also accelerated soil degradation, disrupted nutrient cycles and contributed to water and air pollution, raising concerns for environmental sustainability and food safety. These impacts are particularly acute in intensively managed vegetable systems, where excessive nitrogen and phosphorus inputs, coupled with high irrigation, can impair soil structure, reduce biodiversity and increase greenhouse gas emissions (Chaudhary et al., 2022). In the context of climate change, finite mineral nutrient resources and persistent food insecurity, there is a pressing need for nutrient management strategies that sustain productivity while restoring soil function. Biofertilizers-microbial inoculants that enhance nutrient availability and plant growth-are increasingly viewed as a key component of sustainable intensification pathways for high-value horticultural crops, including vegetables (Mącik et al., 2020).

Biofertilizers are typically defined as formulations containing living or dormant microorganisms that colonize the rhizosphere or plant interior and directly or indirectly stimulate plant growth by improving nutrient acquisition, modulating hormonal balance or protecting against stress and disease (Chaudhary et al., 2022). Common functional groups include nitrogen-fixing bacteria (e.g., Rhizobium, Azotobacter, Azospirillum), phosphate- and potassium-solubilizing microorganisms, plant growth-promoting rhizobacteria (PGPR) and arbuscular mycorrhizal fungi, often applied singly or as consortia (Mącik et al., 2020). These microbes mobilize nutrients through biological nitrogen fixation, solubilization or mineralization of phosphorus and other nutrients, production of siderophores and organic acids, and stimulation of root growth and architecture via phytohormones such as indole-3-acetic acid (Kour et al., 2020). Over the past four decades, research and development have evolved from simple rhizobial inoculants to diverse, microbially enhanced products, including encapsulated formulations and biofilm-based technologies, supported by a rapidly expanding global biofertilizer market driven by demand for organic and residue-free vegetables (Samantaray et al., 2024). Nevertheless, field performance remains variable, influenced by strain selection, formulation quality, application method, soil properties and crop species, underscoring the importance of understanding biofertilizer-soil-plant interactions in specific production systems (Basu et al., 2021).

At the core of biofertilizer function is their impact on soil biological activity, a critical dimension of soil health encompassing the abundance, diversity and functional processes of soil organisms that drive nutrient cycling, organic matter turnover and aggregate formation (Chaudhary et al., 2022). Soil microorganisms, estimated to comprise most of the soil biomass, decompose organic matter, mineralize nutrients, form humus and contribute to soil structure, thereby underpinning soil fertility and plant productivity. Intensive use of mineral fertilizers without sufficient organic inputs can simplify microbial communities, disrupt beneficial interactions and depress key enzymatic activities, whereas inoculation with beneficial microbes, particularly when combined with organic amendments, generally enhances microbial biomass, shifts communities toward more beneficial taxa and increases activities of enzymes such as urease and phosphatases. Meta-analyses and field studies show that biofertilizers can significantly increase soil organic matter, stimulate beneficial bacterial and fungal populations and enhance enzyme activities while suppressing soil-borne pathogens, leading to improved nutrient availability and resilience. Because vegetable systems often experience rapid organic matter decline and biological depletion due to repeated tillage and high nutrient extraction, interventions that revive and stabilize soil biological activity are especially important for maintaining long-term productivity and environmental performance (Mahmud et al., 2021; Medisetti, 2025).

Despite growing evidence that biofertilizers enhance crop yield, nutrient use efficiency and soil quality, relatively fewer studies have focused explicitly on their effects on soil biological activity within intensive vegetable production systems (Basu et al., 2021; Chaudhary et al., 2022). Many quantitative syntheses aggregate across crop types, management regimes and climates, making it difficult to disentangle responses specific to high-input vegetables, which frequently show strong yield responses but may also exhibit distinct soil-biological dynamics due to heavy fertilization and irrigation. Meta-analytical work indicates particularly large yield benefits of biofertilizers in vegetable crops and highlights substantial increases in soil microbial abundance and enzyme activities under biofertilizer use, yet it also points to strong context dependence related to soil fertility status, organic matter content and fertilizer management.

Furthermore, bibliometric analyses reveal that the most recent phase of biofertilizer research increasingly emphasizes their role in improving soil environments and microbiomes, reflecting a shift from solely plant-centered metrics toward integrated soil-plant systems (Mitter et al., 2021). In this context, elucidating how biofertilizers modify soil biological activity-microbial communities, functional groups and enzyme processes-in vegetable production is essential for optimizing formulations and management strategies that simultaneously support high yields, soil health and environmental sustainability. The present study therefore investigates the impact of biofertilizers on soil biological activity in vegetable production systems, aiming to clarify their potential and constraints as core tools in sustainable horticultural nutrient management.

2 Types and Mechanisms of Action of Biofertilizers

2.1 Microbial inoculants

Microbial inoculants are biofertilizer formulations containing live microorganisms-mainly bacteria and fungi-that colonize the rhizosphere, root interior, or phyllosphere to improve plant nutrition and soil health (Mącik et al., 2020). Typical groups include free-living and symbiotic nitrogen fixers (e.g., Azotobacter, Rhizobium), phosphate- and potassium-solubilizing bacteria, cyanobacteria, and arbuscular mycorrhizal fungi, often used singly or as consortia to complement or partially replace synthetic fertilizers (Kour et al., 2020). In vegetable production systems, these inoculants are usually delivered as seed coatings, root dips, soil drenches, or mixed with substrates, and they are increasingly formulated as stable liquid or solid products with protective carriers to ensure viability under intensive management conditions (Fasusi et al., 2021).

Plant growth-promoting rhizobacteria (PGPR) are central to microbial inoculants because they combine nutrient transformations with biostimulant and biocontrol functions (Prisa et al., 2023). Many PGPR strains fix atmospheric nitrogen, solubilize phosphorus, and produce siderophores and hydrolytic enzymes while simultaneously synthesizing phytohormones that stimulate root growth and enhance tolerance to abiotic stress (Mahmud et al., 2021). Field and greenhouse studies show that inoculation with compatible PGPR consortia increases nutrient uptake, microbial biomass, and crop yields in various crops, and can reduce the need for mineral fertilizers without compromising productivity (Shahwar et al., 2023; Nabati et al., 2025). However, performance is strongly context dependent; soil type, native microbiota, crop genotype, and environmental conditions can all influence establishment and function of inoculated strains, underscoring the need for site- and crop-specific inoculant selection in vegetable systems (O'Callaghan et al., 2022).

2.2 Organic biofertilizers and compound biofertilizers

Organic biofertilizers (often termed bio-organic fertilizers) combine decomposed organic materials-such as composts, manures, or agro-industrial wastes-with selected beneficial microorganisms. The organic matrix supplies slow-release nutrients, improves soil structure, and increases organic matter, while also acting as a carrier that supports survival and activity of inoculated microbes after field application. In intensively managed vegetable soils, where repeated tillage and high fertilizer use accelerate organic matter decline, such bio-organic products can restore soil physical properties and provide substrates that stimulate diverse microbial communities, thereby enhancing soil biological activity and nutrient cycling.

Compound biofertilizers extend this concept by integrating multiple functional microbial groups, and in some cases combining them with mineral fertilizers into “microbially enhanced” products (Mącik et al., 2020). For example, formulations may contain nitrogen-fixing bacteria, phosphate-solubilizing microbes, and biocontrol fungi together, designed to act synergistically on nutrient availability, root growth, and disease suppression (Tao et al., 2020). Waste-derived bio-organic fertilizers produced via microbial bioconversion of biomass (e.g., agricultural or food wastes) simultaneously address waste management and nutrient recycling while delivering active microbial consortia to the soil (Elnahal et al., 2022). Studies show that such compound or bio-organic fertilizers can more strongly modify microbial community composition, enrich beneficial taxa such as Bacillus and Pseudomonas, and increase disease-suppressive capacity compared with either organic amendments or single-strain inoculants alone (Tao et al., 2020; Schenk et al., 2024).

2.3 Mechanisms by which biofertilizers enhance soil biological activity

Biofertilizers enhance soil biological activity primarily through biogeochemical mechanisms that increase nutrient availability and energy supply for soil microbes. Core processes include biological nitrogen fixation, solubilization and mineralization of phosphorus and other nutrients, and production of siderophores that chelate iron and stimulate microbial interactions in the rhizosphere (Kour et al., 2020; Timofeeva et al., 2023). By increasing pools of plant-available nitrogen and phosphorus, biofertilizers promote plant growth and root proliferation, which in turn elevates root exudation of carbohydrates, amino acids, and organic acids that serve as energy sources for heterotrophic microbes (Mahmud et al., 2021). This positive feedback increases microbial biomass and activity, often reflected in higher activities of key soil enzymes involved in C, N, and P cycling.

Equally important are ecological and community-level mechanisms through which biofertilizers re-shape soil microbiomes. Inoculation with specific strains or consortia can selectively enrich beneficial microbial groups and alter co-occurrence networks, increasing network stability and functional redundancy (). Bio-organic fertilizers, for instance, have been shown to stimulate indigenous Pseudomonas populations and foster synergistic interactions with inoculated Bacillus, resulting in improved suppression of soil-borne pathogens and a more functionally robust microbial community (Tao et al., 2020; Schenk et al., 2024). Metagenomic analyses further indicate that biofertilizer amendments can increase the abundance of genes involved in nitrogen transformations and plant growth promotion, supporting enhanced nutrient turnover and hormone regulation in the rhizosphere (Aasfar et al., 2021). Through these intertwined biochemical and ecological pathways, biofertilizers rebuild biologically active soils that underpin sustainable, nutrient-efficient vegetable production.

3 Evaluation Indicators of Soil Biological Activity in Vegetable Production Systems

3.1 Soil microbial abundance and community structure

Soil microbial abundance in vegetable systems is commonly quantified using microbial biomass carbon and nitrogen (MBC, MBN) or gene-based proxies such as 16S rRNA and ITS copy numbers. In long-term organic vegetable production, frequent cover cropping and organic matter inputs can raise MBC to relatively high levels for sandy soils, and MBN responds in parallel, highlighting biomass as a sensitive integrator of management effects on soil biology. Global comparisons further show that microbial biomass and diversity covary strongly with soil carbon content, so shifts in soil organic matter under intensive fertilization or organic amendments directly influence biomass-based indicators (Bastida et al., 2021). These metrics therefore provide a robust, quantitative basis for assessing how biofertilizers and organic inputs modify the "size" of the active microbial community in vegetable systems.

Community structure and diversity indicators complement biomass data by revealing how taxa respond to intensive vegetable cultivation and management. High-throughput sequencing of greenhouse vegetable soils has shown that continuous cultivation can reduce bacterial and fungal richness and alter dominant phyla, with declines in OTU abundance and diversity after several years of high-input production. Conversely, agroecological and organic vegetable systems that include mulches, composts, or cover crops tend to increase bacterial and fungal diversity and shift communities toward beneficial groups such as Actinobacteria and other decomposers, changes that correlate with improved soil nutrients and organic matter (Moulin et al., 2023). Together, microbial biomass and community composition form core indicators to evaluate the impact of biofertilizers on soil biological activity and ecological resilience in vegetable production.

3.2 Soil Enzyme activity indicators

Soil enzyme activities provide functional indicators of microbial processes underpinning nutrient cycling and are widely used to assess soil quality in agroecosystems. Hydrolases such as urease, phosphatases, and β-glucosidase are particularly informative because they catalyze key steps in nitrogen, phosphorus, and carbon turnover and respond sensitively to changes in management, organic matter, and disturbance (Jat et al., 2021). Reviews emphasize that these enzymes are operationally practical and more responsive to tillage and structure modification than many physicochemical variables, making them useful early-warning indicators of biological changes in intensively managed soils (Attademo et al., 2021). In vegetable systems where biofertilizers and organic amendments are applied to improve fertility, monitoring these enzymes can directly reflect enhanced mineralization and nutrient availability.

Field and long-term management studies confirm that enzyme activities differentiate contrasting fertility regimes and cropping strategies. Under climate-smart cereal rotations, dehydrogenase, β-glucosidase, phosphatases, urease, and other enzymes vary significantly with management scenario, crop growth stage, and rhizosphere versus bulk soil, and are strongly regulated by soil organic carbon (Raimi et al., 2023). In vegetable-based systems, organic fertilization and manure inputs generally increase activities of dehydrogenase, β-glucosidase, and urease compared with conventional fertilization, with enzyme responses closely tied to microbial biomass and organic matter content (Antonious et al., 2020; Raimi et al., 2023). Because biofertilizers often supply both functional microbes and substrates, increases in these enzyme activities serve as key indicators that soil biological functioning and nutrient cycling capacity have been stimulated.

3.3 Soil respiration and microbial biomass carbon and nitrogen

Soil respiration, measured as CO_2 efflux, is a central indicator of overall microbial metabolic activity and carbon turnover. Seasonal monitoring in agricultural soils shows that microbial respiration tracks temperature and plant presence, with higher rates where soil organic carbon is greater and fresh residues are retained (Schnecker et al., 2023). In organic vegetable systems with frequent cover cropping or compost additions, soil respiration and related metrics such as the metabolic quotient often increase, reflecting enhanced decomposition and active microbial communities fueled by larger carbon inputs (Antonious et al., 2020). However, interpreting respiration alone can be misleading, so it is most informative when combined with microbial growth or biomass data to distinguish efficient biomass production from rapid C loss.

Microbial biomass C and N are therefore indispensable complementary indicators, capturing the living pool of microbial cells that mediate nutrient cycling. In multi-cropping and organic vegetable experiments across Europe, microbial C and N (Cmic, Nmic) increase under diversified cropping and higher organic inputs, and their stoichiometric ratios (Cmic/Nmic, Cmic/TOC) are used to infer shifts in nutrient limitation and carbon stabilization potential (Figure 1) (Trinchera et al., 2022). Global analyses reveal that the relationship between microbial diversity and biomass is strongly governed by soil carbon, underscoring how management-driven changes in organic matter, including biofertilizer use, cascade into microbial standing stocks and functions (Bastida et al., 2021; Schnecker et al., 2023). Consequently, integrating soil respiration with microbial biomass C and N provides a powerful set of indicators to evaluate how biofertilizers influence both the intensity and efficiency of microbial activity in vegetable production soils.

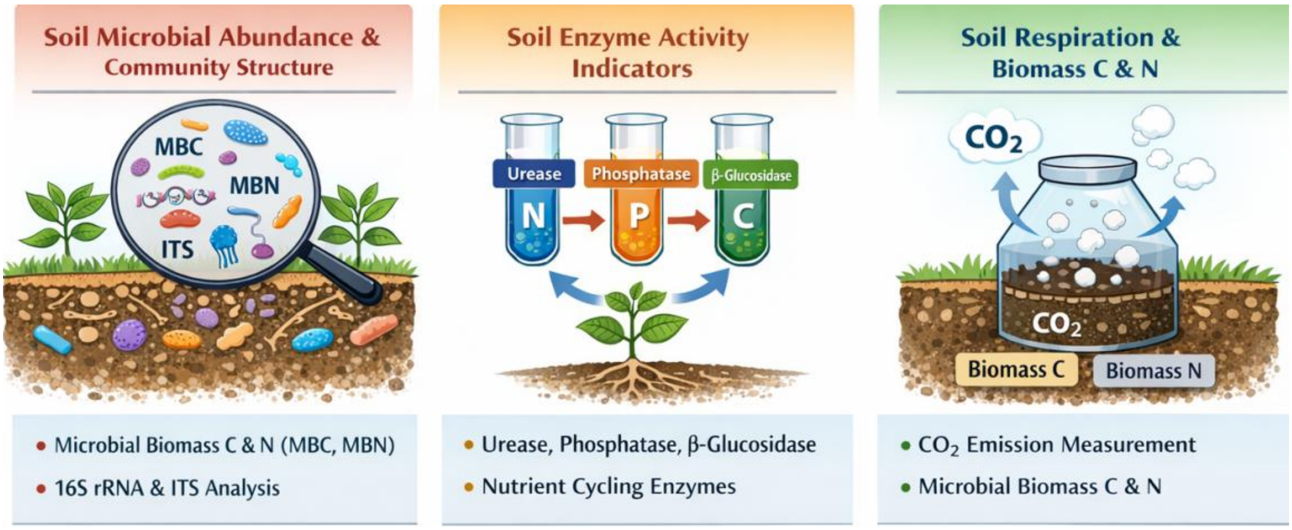

Figure 1 Evaluation indicators of soil biological activity in vegetable production systems

4 The Impact of Biofertilizers on Soil Microbial Community Structure

4.1 Changes in microbial diversity

Biofertilizers frequently alter α-diversity (richness and evenness) and β-diversity (community dissimilarity) of soil and rhizosphere microbiota in vegetable and other cropping systems. In greenhouse cucumber, different biofertilizers applied to soil or substrate significantly modified bacterial and fungal diversity over the season, with distinct community trajectories between fertilized and unfertilized treatments (Wu et al., 2022). In maize, Bacillus-based biofertilizers generally increased rhizosphere bacterial richness and diversity relative to the control, although consortia of multiple strains sometimes reduced overall diversity, suggesting a directional enrichment of specific functional taxa at the expense of community evenness (Wang et al., 2021; Zhang et al., 2025).

Patterns are not universally positive for diversity, underscoring that biofertilizers reshape communities rather than simply “add” diversity. A Bacillus bio-organic fertilizer applied to pakchoi reduced both bacterial and fungal diversity compared with unfertilized soil, while strongly shifting composition and enriching particular beneficial groups (Tao et al., 2020). Actinobacterial biofertilizers containing Streptomyces spp. likewise altered fungal community composition and co-occurrence networks across several crops without consistently increasing bacterial or fungal α-diversity, indicating that functional reassembly can occur even when richness is stable (Li et al., 2022; Zhao et al., 2022). These results highlight that diversity responses depend on formulation, dosage, and substrate, but shifts in β-diversity and taxonomic structure are almost ubiquitous following biofertilizer application.

4.2 Regulatory roles of dominant functional microbial groups

A central ecological effect of biofertilizers is the enrichment or suppression of dominant functional groups that drive nutrient cycling and plant health. Bacillus- and Trichoderma-amended biofertilizers increase the relative abundance of plant-beneficial bacteria and fungi, including Bacillus, Rhodanobacter, Massilia, Trichoderma, and

Penicillium, thereby enhancing soil fertility, nutrient cycling, and crop yields in cereal-legume systems (Figiel et al., 2025). In maize rhizospheres, Bacillus biofertilizers increase organic matter and available N, P, and K, while maintaining high abundances of Proteobacteria, Actinobacteria, and Acidobacteria and enriching bacterial functions related to amino-acid, sugar, and energy metabolism (Wang et al., 2021).

Other formulations shift dominance toward disease-suppressive or nutrient-transforming guilds. Bio-organic fertilizers containing Bacillus amyloliquefaciens stimulate indigenous Pseudomonas populations and promote synergistic biofilm-forming consortia that suppress Fusarium wilt in banana, illustrating how an inoculant can act indirectly through native keystone taxa (Tao et al., 2020; Kumar et al., 2021). Streptomyces-based biofertilizers increase beneficial bacterial genera such as Chitinophaga and Pseudoxanthomonas while decreasing phytopathogenic fungi including Cladosporium and Gibberella, and they reduce microbial network connectivity, indicating re-wiring of interaction networks and keystone roles for introduced actinobacteria (Li et al., 2022; Zhao et al., 2022). Collectively, these findings show that dominant functional groups-PGPR, actinobacteria, saprotrophic and biocontrol fungi-are pivotal levers through which biofertilizers regulate community structure and ecosystem functioning.

4.3 Improvement of the rhizosphere micro-ecological environment

Biofertilizers modify the rhizosphere micro-environment by simultaneously changing soil physicochemical properties, root exudation, and microbial interactions. In maize, Bacillus biofertilizers increase soil organic matter, total N and P, and available P and K, likely by stimulating plant root exudates that recruit beneficial bacteria and enhance nutrient dissolution, thereby reshaping community structure through resource-driven selection (Wang et al., 2021). In greenhouse cucumber, different biofertilizers applied to soil or substrate improve plant growth and reduce soil-borne pathogens, with time-dependent shifts in rhizosphere bacterial and fungal communities that reflect altered nutrient availability and microhabitat conditions around the roots (Wu et al., 2022).

Bio-organic and microbial fertilizers also foster hizosphere environments characterized by higher abundances of beneficial taxa and enhanced soil functionality. In pakchoi, a Bacillus bio-organic fertilizer increases soil pH and available K while enriching beneficial bacteria and saprotrophic fungi, and network analysis indicates that Bacillus acts as a hub stimulating colonization by other advantageous microbes in the rhizosphere (Wang et al., 2022). Actinobacterial biofertilizers applied across multiple crops increase yields by up to ~50% and shift rhizosphere fungal assemblages and assembly processes, while metagenomic and modeling work in biofertilizer-amended soils shows enrichment of genes for nitrogen transformation and plant growth promotion, supporting a more functionally complementary and nutrient-efficient rhizosphere microbiome (Li et al., 2022; Figiel et al., 2025). These micro-ecological improvements help explain the consistent links between biofertilizer-induced community modulation, enhanced soil biological activity, and improved crop performance.

5 The Impact of Biofertilizers on Soil Enzyme Activity and Metabolic Functions

5.1 Patterns of change in key enzyme activities

Biofertilizers consistently enhance a suite of extracellular enzymes that mediate nutrient release from organic and inorganic pools. A large field meta-analysis in China reported mean increases in urease and phosphatase activities of 57.6% and 43.5%, respectively, together with significant stimulation of sucrase and catalase following biofertilizer application across multiple crops, including vegetables (Pei et al., 2025). In a wheat-maize rotation, partial substitution of NPK with biofertilizer significantly increased urease, alkaline phosphatase, and sucrase activities at key growth stages, with the optimal blend (60% NPK + 20% biofertilizer) giving the largest and most persistent increases, indicating that moderate biofertilizer inputs most efficiently stimulate soil biochemical functioning (Ali et al., 2024).

Targeted studies on contaminated or degraded soils show similar directional responses in a broader enzyme suite. In heavy-metal-impacted greenhouse soils, Pseudomonas and Bacillus-based biofertilizers markedly increased urease, dehydrogenase, alkaline phosphatase, β-D-glucosidase, and arylsulfatase activities relative to the untreated control, with statistically significant treatment and dose effects for each enzyme (Haroun et al., 2023). Long-term vegetable experiments comparing compost, chemical fertilizer, and no fertilizer demonstrate that compost-based organic fertilization-functionally analogous to many bio-organic fertilizers-substantially enhances dehydrogenase, β-glucosidase, protease, urease, arylsulfatase, and acid/alkaline phosphatases, and that enzyme activities correlate strongly and linearly with soil organic matter content.

5.2 Responses of enzymes related to carbon and nitrogen cycling

Enzymes involved in carbon acquisition, such as β-glucosidase and related glycosidases, frequently increase under biofertilizer or biochar-based fertilizer regimes, reflecting enhanced decomposition and turnover of plant residues and organic amendments. In a wheat-maize system, biofertilizer additions significantly elevated sucrase activity, interpreted as a sign of stimulated microbial metabolism and accelerated organic matter decomposition in maize soils (Ali et al., 2024). Long-term substitution of conventional fertilizer with biochar-based fertilizer increased activities of α-glucosidase, N-acetyl-β-D-glucosidase, and leucine aminopeptidase, with these C- and N-acquiring enzymes tightly linked to improved soil quality indices and higher maize yields, underscoring the central role of enzyme-mediated C and N cycling in productivity gains (Wang et al., 2025).

Nitrogen-cycling enzymes and associated processes also respond strongly to biologically enriched fertilization. The China-wide meta-analysis showed that biofertilizer use increased nitrification rates by over 70%, in parallel with the large increases in urease activity, and reduced ammonium losses, indicating more complete and efficient N mineralization and transformation in the soil-plant system (Pei et al., 2025). A global meta-analysis of biochar field trials further demonstrated that biochar application significantly enhanced N mineralization, nitrification, and N fixation as well as N-acetyl-glucosaminidase activity, while simultaneously increasing the abundance of key nitrification and denitrification genes (amoA, narG, nirS/nirK, nosZ), confirming that enzyme stimulation is coupled with upregulation of microbial N-cycling potential under organic-rich amendments (Zhang et al., 2021).

5.3 Enhancement of soil nutrient transformation efficiency

By jointly stimulating enzyme activities and reshaping microbial communities, biofertilizers improve the efficiency with which soils transform and retain nutrients. Across 107 field studies, biofertilizers increased total soil N by about 16.7% and available P by 11.0%, while markedly boosting urease and phosphatase activities, reducing nitrate losses, and lowering electrical conductivity, a pattern interpreted as more efficient N and P cycling together with improved ionic balance and organic matter accumulation (Pei et al., 2025). Metagenomic analysis of soils amended with a bacterial biofertilizer showed 46.7% and 88.6% increases in fast-acting (available) N and P, respectively, along with enrichment of nitrification genes and plant growth-promotion traits, indicating that nutrient transformation efficiency is enhanced through both biochemical (enzyme) and genetic (functional gene) pathways (Li et al., 2023).

Biofertilizer and organic-amendment strategies in intensive vegetable and arable systems can also alter ecoenzymatic stoichiometry, shifting microbial resource limitation and thereby optimizing nutrient capture. In greenhouse tomato soils, diverse organic materials (including biochar and manure) reduced C limitation while increasing microbial N demand, with biochar particularly effective at enhancing C-, N-, and P-acquiring enzyme activities and organic C sequestration across soil types (-). Studies of enzyme stoichiometry and N management in semi-arid croplands further show that fertilization regimes which intensify microbial P limitation can down-regulate the abundance of nitrification and denitrification genes, constraining N losses via gaseous pathways and highlighting how managing enzyme-mediated nutrient demand can be leveraged to synchronize N availability with crop uptake and reduce environmental leakage (Cui et al., 2020).

6 Indirect Impacts of Biofertilizers on Vegetable Yield and Quality

6.1 The relationship between soil biological activity and crop growth

Enhanced soil biological activity is a central pathway through which biofertilizers indirectly stimulate vegetable growth. A large meta-analysis in China showed that biofertilizers increased soil organic matter, boosted urease and phosphatase activities, and promoted beneficial microbial populations, while suppressing pathogens; these shifts in biological functioning were closely associated with higher root volume and reduced disease incidence, explaining much of the observed yield response across crops including vegetables (Pei et al., 2025). A global meta-analysis similarly linked biofertilizer use with improved nitrogen and phosphorus use efficiency, highlighting that microbial inoculants enhance plant access to soil and fertilizer nutrients, particularly under suboptimal resource conditions, thereby supporting more vigorous crop growth for a given external input level.

System-level vegetable experiments further confirm that more active soil microbial communities translate into improved crop performance. In an intensified organic vegetable rotation using plant-based fertilizers, cover crops, and reduced tillage, β-glucosidase and dehydrogenase activities and potential N mineralization were markedly higher than under common practice, and these improvements in microbial activity coincided with 1.3-2.7-fold increases in marketable yields and greater plant N uptake without increasing N leaching risk (Hefner et al., 2023). A broader systematic review on microbial activity and nutrient cycling likewise concluded that most studies report microbial-driven enhancement of soil fertility and crop productivity, supporting the view that managing soil microbes is a powerful lever for sustaining growth in intensive systems such as vegetable production (Bayu, 2024).

6.2 Promoting effects on vegetable yield

Across crops and environments, biofertilizers consistently promote yield, with particularly strong effects documented for vegetables. A comprehensive Chinese meta-analysis found that biofertilizers increased yields for 21 of 23 crops, with vegetables such as Chinese cabbage and ginger showing gains of roughly 36-39%, attributing these responses to improved nutrient availability, better root growth, and reduced disease incidence (Pei et al., 2025). A global synthesis of field trials reported average yield increases of around 8-20% depending on climate, and showed that combinations of N-fixers, P-solubilizers and mycorrhiza are especially effective when soil phosphorus is not severely limiting, underscoring that yield benefits depend on matching microbial traits to soil conditions.

Vegetable-focused experiments under greenhouse and field conditions provide more specific evidence for yield promotion and fertilizer savings. In lettuce and broccoli, treatments combining biofertilizer with full or reduced chemical fertilizer rates achieved total and marketable yields comparable to or higher than full mineral fertilization alone, indicating that biofertilizers can maintain productivity while allowing 50% reduction in chemical NPK inputs (Demir et al., 2023). For Swiss chard, vermicompost-functionally analogous to many bio-organic fertilizers-applied alone or with biochar increased yield by about 140% relative to untreated or biochar-only soils, demonstrating that biologically active organic amendments can match mineral N in supporting high productivity while simultaneously improving soil quality (Libutti et al., 2023).

6.3 Impacts on quality

Biofertilizers indirectly enhance vegetable quality by improving plant nutrition and reducing physiological imbalances such as excessive nitrate accumulation. In the Chinese field meta-analysis, biofertilizer application significantly increased vitamin C, protein, and carotenoid contents while decreasing nitrate concentrations by about 22%, indicating that microbial inoculants can shift the balance toward more nutrient-dense and safer produce across a wide range of crops (Pei et al., 2025). A review on biofertilizers and food security similarly reported crop yield increases of 10%-40% accompanied by higher protein, essential amino acids, and vitamins, emphasizing that microbially mediated nutrient mobilization often improves nutritional profiles rather than simply increasing biomass (Daniel et al., 2022).

Recent vegetable studies confirm these quality effects under practical cultivation scenarios. In tomato, brinjal, and okra, replacing part of the chemical fertilizer with diverse organic sources plus a microbial consortium increased soil microbial populations and improved nutritional, organoleptic, and nutraceutical attributes, including higher antioxidant contents, relative to conventional fertilization alone (Bhardwaj et al., 2025). In Swiss chard, vermicompost and its mixtures with biochar not only raised yield but also increased specialized metabolites and antioxidant activity, while keeping leaf nitrate within regulatory safety thresholds, illustrating that biologically enriched fertilization can simultaneously support high productivity, nutritional quality, and nitrate safety in leafy vegetables (Libutti et al., 2023).

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7 Case Study

7.1 Experimental design for biofertilizer application on a typical vegetable crop

A representative case study can be framed around field-grown tomato under conventional fertilization contrasted with a regime where mineral inputs are partially replaced by a Trichoderma-enriched bio-organic fertilizer. Ye et al. evaluated four fertilization strategies: full-rate chemical fertilizer (CF, 100% conventional NPK), reduced chemical fertilizer plus Trichoderma bio-organic fertilizer (75% NPK + BF), reduced NPK plus uninoculated organic fertilizer (OF), and reduced NPK plus Trichoderma spore suspension alone (SS), allowing isolation of microbial, organic-matter, and combined effects under realistic agronomic conditions (Ye et al., 2020). Experimental plots were arranged in a randomized design with multiple replicates, and both field and pot trials were implemented to capture responses across soil environments while controlling for confounding variation in microclimate and root-zone conditions (Ye et al., 2020).

A similar structure can be adapted for cucumber within organic or low-input systems, where biofertilizer is applied either via soil, foliar spray, or both. For instance, a randomized block 6 × 2 factorial design was used to test six concentrations of a liquid plant-based biofertilizer (0-5% in water) combined with presence or absence of soil application in organically grown Aodai cucumber, with four replications and eight plants per plot to ensure adequate statistical power (Da Silva Tamwing et al., 2020). Biofertilizer was applied at sowing to the soil and then at 7-day intervals via foliar sprays up to 28 days after sowing, with yield-related traits (fruit number, mean fruit mass, marketable yield) and morphological parameters (fruit length, diameter) measured at each harvest (Da Silva Tamwing et al., 2020). This kind of design, incorporating factorial combinations of dose and application pathway, is directly transferable to other greenhouse vegetable crops and enables optimization of biofertilizer regimes (Figure 2).

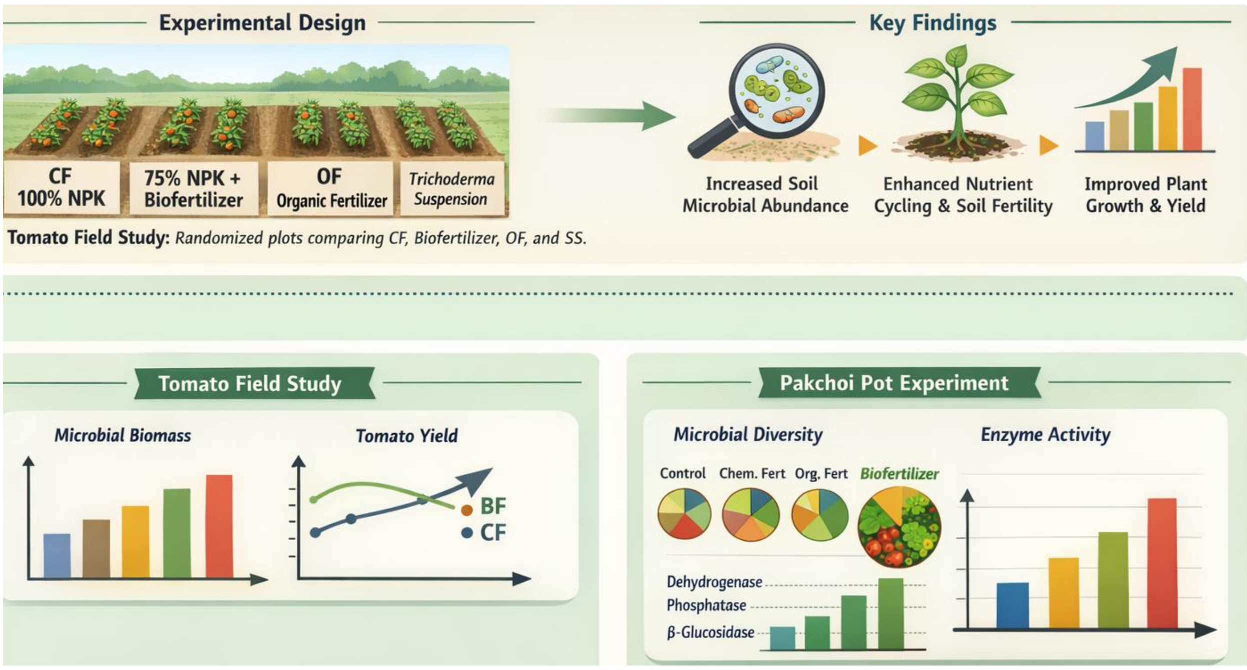

Figure 2 Experimental designs and key outcomes of biofertilizer application in vegetable crops

7.2 Changes in soil biological activity and data analysis

In the tomato case, reduced chemical fertilizer plus Trichoderma bio-organic fertilizer induced measurable shifts in soil biological activity relative to full mineral fertilization. Ye et al. observed that the BF treatment substantially increased soil microbial abundance and improved indices of soil fertility compared with CF, with many soil biological parameters showing significant positive linear relationships with yield, suggesting that enhanced microbial activity and community size mediated the agronomic response (Ye et al., 2020). In addition, correlations between microbial abundance and soil nutrient pools in BF-treated soils suggested a tighter coupling of mineralization and plant demand, helping to stabilize yields despite a 25% reduction in mineral inputs.

A complementary view comes from pakchoi grown in pots with four fertilization treatments: control (no input), chemical fertilizer, organic fertilizer, and a Bacillus-containing bio-organic fertilizer (BF). After 30 days, BF treatment significantly increased plant height and biomass and raised soil available potassium and pH relative to unfertilized soil, while high-throughput sequencing revealed a marked restructuring of bacterial and fungal communities, including enrichment of beneficial genera such as Streptomyces and Mortierella (Wang et al., 2022). Network and functional predictions indicated that BF promoted bacterial dominance, enhanced mineral element metabolism, and increased saprotrophic fungi, supporting a mechanistic link between inoculant addition, microbial community assembly, and nutrient-related enzyme functions in the rhizosphere (Wang et al., 2022). Together, these results illustrate that case-study designs can combine agronomic measurements with molecular and biochemical indicators to quantify changes in soil biological activity.

7.3 Evaluation of application effectiveness and practical significance

Evaluation of application effectiveness in tomato systems centers on whether biofertilizers can maintain yield while reducing mineral fertilizer and simultaneously improve fruit quality. Under field and pot conditions, the combination of 75% conventional NPK with Trichoderma-enriched bio-organic fertilizer produced tomato yields equivalent to those achieved with 100% NPK alone, demonstrating that a quarter of the chemical fertilizer could be saved without yield penalty (Ye et al., 2020). Moreover, the BF treatment significantly increased total soluble sugars and vitamin C by up to 24% and 57%, respectively, while reducing nitrate accumulation by as much as 62% relative to CF, implying substantial gains in nutritional value and safety that go beyond mere yield maintenance. From an environmental and economic standpoint, such a regime reduces reliance on synthetic fertilizers, lowers potential nitrate leaching and residue risks, and can improve marketability due to enhanced quality traits.

Cucumber case studies in organic systems highlight the capacity of plant-based biofertilizers to raise productivity through optimized foliar dosing. In Aodai cucumber, foliar application of a plant-residue biofertilizer significantly increased the number of marketable fruits per plant, mean fruit mass, and both marketable and total yields, with a 3% solution identified as the most efficient concentration for yield enhancement under the tested conditions (Da Silva Tamwing et al., 2020). The authors attributed the effectiveness of foliar application to rapid leaf uptake of macro- and micronutrients and the stimulation of plant defense metabolism, which reduced the need for additional pest and disease control interventions during the cycle. Collectively, these tomato and cucumber case studies suggest that, when appropriately formulated and combined with moderate mineral or organic inputs, biofertilizers can be practically significant tools for improving soil biological activity, sustaining or increasing yields, and enhancing vegetable quality within sustainable production systems.

8 Conclusion and Outlook

Research over the past decades shows that biofertilizers are central to linking soil biological activity with crop productivity. Microbial inoculants such as plant growth-promoting rhizobacteria, arbuscular mycorrhizal fungi, and microbial consortia enhance nutrient availability, modulate phytohormones, and improve plant tolerance to abiotic and biotic stresses, thereby supporting higher yields with lower dependence on synthetic fertilizers. Global and national meta-analyses confirm that, under field conditions, biofertilizers significantly increase yields across many crops, including vegetables, while also improving soil enzymatic activities, organic matter, and the abundance of beneficial microbial groups that underpin long-term soil fertility.

In vegetable systems, biofertilizers and bio-organic formulations improve not only productivity but also nutritional quality and safety, largely through soil-mediated effects. Field synthesis for China shows that biofertilizer application increases vitamin C, protein, and carotenoids while reducing nitrate accumulation, and these quality gains coincide with higher soil urease and phosphatase activities and a shift toward beneficial microbiota. Case studies and reviews focused on vegetable crops similarly highlight that combining biofertilizers with organic amendments and/or reduced mineral fertilization enhances soil biota diversity and supports sustainable vegetable production, providing a viable pathway to reconcile yield goals with environmental protection.

Despite clear benefits, field performance of biofertilizers remains inconsistent, especially under diverse soil and climate conditions typical of vegetable production regions. Meta-analytical and review work emphasizes that the effectiveness of a given inoculant depends strongly on crop species, soil physicochemical properties, native microbiota, and climate; strain-environment mismatches can result in weak or negligible responses under farmer conditions. Large-scale field syntheses also caution that current data mostly reflect real-world but sub-optimal formulations and management, implying that observed benefits may underestimate biological potential while still displaying substantial variability across sites and crops.

A second major challenge is the translation of laboratory and greenhouse successes into robust, scalable technologies suitable for commercial vegetable systems. Reviews on formulation and commercialization highlight that poor survival of inoculants during storage, transport, and application, lack of quality control, and inadequate regulatory frameworks all contribute to variable outcomes and limited farmer trust. Regional assessments (e.g., Iran) further show that low soil organic matter, strong reliance on chemical fertilizers, and weak coordination among research, industry, and extension institutions have slowed adoption, underscoring that socio-economic and institutional bottlenecks are as important as technical ones.

Future work on biofertilizers in vegetable production needs to integrate multi-omics and systems approaches with agronomic experimentation to better match strains, formulations, and management to specific soils and crops. Advances in metagenomics, transcriptomics, and metabolomics are already clarifying how microbial consortia assemble in the rhizosphere and influence nutrient cycling; leveraging these tools can guide the design of targeted, crop and region specific biofertilizers with improved colonization and function. Large meta-analyses also suggest that trait-based selection (e.g., N fixation, P solubilization, stress tolerance) aligned with soil P levels, organic matter content, and pH can markedly increase success rates, providing a quantitative framework for precision biofertilization in intensive vegetable systems.

At the application level, research should prioritize long-term field trials in vegetable rotations, testing integrated strategies that combine microbial consortia with organic amendments, reduced mineral fertilization, and agroecological designs (e.g., push-pull, diversified rotations). Recent reviews argue that coupling biofertilizers with such systems can enhance soil health, pest regulation, and resilience to climate stresses, but require refined delivery methods, robust formulation technologies, and stringent quality control to ensure consistent performance . Strengthening links between microbiologists, agronomists, industry, and extension services will be crucial for scaling up these innovations, improving farmer awareness, and positioning biofertilizers as cornerstone inputs for climate-smart, high-quality vegetable production.

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Conflict of Interest Disclosure

The author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

References

Aasfar A., Bargaz A., Yaakoubi K., Hilali A., Bennis I., Zeroual Y., and Kadmiri I.M., 2021, Nitrogen fixing Azotobacter species as potential soil biological enhancers for crop nutrition and yield stability, Frontiers in Microbiology, 12: 628379. https://doi.org/10.3389/fmicb.2021.628379

Ali A., Liu X., Yang W., Li W., Chen J., Qiao Y., Gao Z., and Yang Z., 2024, Impact of bio-organic fertilizer incorporation on soil nutrients, enzymatic activity, and microbial community in wheat-maize rotation system, Agronomy, 14(9): 1942. https://doi.org/10.3390/agronomy14091942

Antonious G.F., Turley E.T., and Dawood M.H., 2020, Monitoring soil enzymes activity before and after animal manure application, Agriculture, 10(5): 166. https://doi.org/10.3390/agriculture10050166

Attademo A.M., Sanchez-Hernandez J.C., Lajmanovich R.C., Repetti M.R., and Peltzer P.M., 2021, Enzyme activities as indicators of soil quality: response to intensive soybean and rice crops, Water, Air, & Soil Pollution, 232: 274. https://doi.org/10.1007/s11270-021-05211-2

Bastida F., Eldridge D.J., García C., Png G.K., Bardgett R.D., and Delgado-Baquerizo M., 2021, Soil microbial diversity-biomass relationships are driven by soil carbon content across global biomes, The ISME Journal, 15(7): 2081-2091.
https://doi.org/10.1038/s41396-021-00906-0

Basu A., Prasad P., Das S.N., Kalam S., Sayyed R.Z., Reddy M.S., and El Enshasy H., 2021, Plant growth promoting rhizobacteria (PGPR) as green bioinoculants: recent developments, constraints, and prospects, Sustainability, 13(3): 1140.
https://doi.org/10.3390/su13031140

Bayu T., 2024, Systematic review on the role of microbial activities on nutrient cycling and transformation implication for soil fertility and crop productivity, bioRxiv: 2024.09.02.610905.
https://doi.org/10.1101/2024.09.02.610905

Bhardwaj R., Vyas L., Verma M., Meena S.K., Chattopadhyay A., Meena N.K., Jakhar D.S., and Kumawat S., 2025, Increasing productivity and recovering nutritional, organoleptic, and nutraceutical qualities of major vegetable crops for better dietetics, Foods, 14(2): 254.
https://doi.org/10.3390/foods14020254

Chaudhary P., Singh S., Chaudhary A., Sharma A., and Kumar G., 2022, Overview of biofertilizers in crop production and stress management for sustainable agriculture, Frontiers in Plant Science, 13: 930340.
https://doi.org/10.3389/fpls.2022.930340

Cui Y., Zhang Y., Duan C., Wang X., Zhang X., Ju W., Chen H., Yue S., Wang Y., Li S., and Fang L., 2020, Ecoenzymatic stoichiometry reveals microbial phosphorus limitation decreases the nitrogen cycling potential of soils in semi-arid agricultural ecosystems, Soil and Tillage Research, 197: 104463.
https://doi.org/10.1016/j.still.2019.104463

Da Silva Tamwing G.D., de Araújo Neto S.E., Marino G., Marreiro A.S., and Ferreira R.L.F., 2020, Cucumber production under organic cultivation in response to biofertilizer application, Comunicata Scientiae, 11: e3443.
https://doi.org/10.14295/cs.v11i.3443

Daniel A.I., Fadaka A.O., Gokul A., Bakare O.O., Aina O., Fisher S., Burt A.F., Mavumengwana V., Keyster M., and Klein A., 2022, Biofertilizer: the future of food security and food safety, Microorganisms, 10(6): 1220.
https://doi.org/10.3390/microorganisms10061220

Demir H., Sönmez İ., Uçan U., and Akgün I., 2023, Biofertilizers improve the plant growth, yield, and mineral concentration of lettuce and broccoli, Agronomy, 13(8): 2031.
https://doi.org/10.3390/agronomy13082031

Fasusi O.A., Cruz C., and Babalola O.O., 2021, Agricultural sustainability: microbial biofertilizers in rhizosphere management, Agriculture, 11(2): 163.
https://doi.org/10.3390/agriculture11020163

Figiel S., Rusek P., Ryszko U., and Brodowska M.S., 2025, Microbially enhanced biofertilizers: technologies, mechanisms of action, and agricultural applications, Agronomy, 15(5): 1191.
https://doi.org/10.3390/agronomy15051191

Haroun M., Xie S., Awadelkareem W., Wang J., and Qian X., 2023, Influence of biofertilizer on heavy metal bioremediation and enzyme activities in the soil to revealing the potential for sustainable soil restoration, Scientific Reports, 13: 18137.
https://doi.org/10.1038/s41598-023-44986-8

Hefner M., Gebremikael M.T., and Kristensen H.L., 2023, Soil microbial activity improved while intensifying vegetable production by use of plant-based fertilisers, cover crops and reduced tillage, Pedobiologia, 99-100: 150926.
https://doi.org/10.1016/j.pedobi.2023.150926

Jat H.S., Datta A., Choudhary M., Sharma P.C., Dixit B., and Jat M.L., 2021, Soil enzymes activity: effect of climate smart agriculture on rhizosphere and bulk soil under cereal based systems of north-west India, European Journal of Soil Biology, 103: 103292.
https://doi.org/10.1016/j.ejsobi.2021.103292

Jin N., Jin L., Wang S., Li J., Liu F., Liu Z., Luo S., Wu Y., Lyu J., and Yu J., 2022, Reduced chemical fertilizer combined with bio-organic fertilizer affects the soil microbial community and yield and quality of lettuce, Frontiers in Microbiology, 13: 863325.
https://doi.org/10.3389/fmicb.2022.863325

Kour D., Rana K.L., Yadav A.N., Yadav N., Kumar M., Kumar V., Vyas P., Dhaliwal H.S., and Saxena A.K., 2020, Microbial biofertilizers: bioresources and eco-friendly technologies for agricultural and environmental sustainability, Biocatalysis and Agricultural Biotechnology, 23: 101487.
https://doi.org/10.1016/j.bcab.2019.101487

Kumar S.D., Sindhu S.S., and Kumar R., 2022, Biofertilizers: an ecofriendly technology for nutrient recycling and environmental sustainability, Current Research in Microbial Sciences, 3: 100094.
https://doi.org/10.1016/j.crmicr.2021.100094

Libutti A., Russo D., Lela L., Ponticelli M., Milella L., and Rivelli A.R., 2023, Enhancement of yield, phytochemical content and biological activity of a leafy vegetable (Beta vulgaris L. var. cycla) by using organic amendments as an alternative to chemical fertilizer, Plants, 12(3): 569.
https://doi.org/10.3390/plants12030569

Mącik M., Gryta A., and Frąc M., 2020, Biofertilizers in agriculture: an overview on concepts, strategies and effects on soil microorganisms, Advances in Agronomy, 162: 31-87.
https://doi.org/10.1016/bs.agron.2020.02.001

Mahmud A.A., Upadhyay S.K., Srivastava A.K., and Bhojiya A.A., 2021, Biofertilizers: a nexus between soil fertility and crop productivity under abiotic stress, Current Research in Environmental Sustainability, 3: 100063.

Medisetti N., 2025, The impact of bio-fertilizers on vegetable crops, International Journal of Advanced Research, 13(6): 1335-1340.

Mitter E.K., Tosi M., Obregón D., Dunfield K.E., and Germida J.J., 2021, Rethinking crop nutrition in times of modern microbiology: innovative biofertilizer technologies, Frontiers in Sustainable Food Systems, 5: 606815.
https://doi.org/10.3389/fsufs.2021.606815

Moulin C., Pruneau L., Vaillant V., and Loranger-Merciris G., 2023, Impacts of agroecological practices on soil microbial communities in experimental open-field vegetable cropping systems, FEMS Microbiology Ecology, 99(5): fiad030.
https://doi.org/10.1093/femsec/fiad030

Nabati J., Nezami A., Yousefi A.R., Oskoueian E., Oskoueian A., and Ahmadi-Lahijani M.J., 2025, Biofertilizers containing plant growth promoting rhizobacteria enhance nutrient uptake and improve the growth and yield of chickpea plants in an arid environment, Scientific Reports, 15: 93070.
https://doi.org/10.1038/s41598-025-93070-w

Nosheen S., Ajmal I., and Song Y., 2021, Microbes as biofertilizers, a potential approach for sustainable crop production, Sustainability, 13(4): 1868.
https://doi.org/10.3390/su13041868

O'Callaghan M., Ballard R.A., and Wright D., 2022, Soil microbial inoculants for sustainable agriculture: limitations and opportunities, Soil Use and Management, 38(3): 1340-1369.
https://doi.org/10.1111/sum.12811

Pei B., Liu T., Xue Z., Cao J., Zhang Y., Yu M., Liu E., Xing J., Wang F., Ren X., and Zhang Z., 2025, Effects of biofertilizer on yield and quality of crops and properties of soil under field conditions in China: a meta-analysis, Agriculture, 15(10): 1066.
https://doi.org/10.3390/agriculture15101066

Prisa D., Fresco R., and Spagnuolo D., 2023, Microbial biofertilisers in plant production and resistance: a review, Agriculture, 13(9): 1666.
https://doi.org/10.3390/agriculture13091666

Raimi A., Ezeokoli O.T., and Adeleke R., 2023, Soil nutrient management influences diversity, community association and functional structure of rhizosphere bacteriome under vegetable crop production, Frontiers in Microbiology, 14: 1229873.
https://doi.org/10.3389/fmicb.2023.1229873

Samantaray A., Chattaraj S., Mitra D., Ganguly A., Kumar R., Gaur A., Mohapatra P.K.D., Santos-Villalobos S., Rani A., and Thatoi H., 2024, Advances in microbial based bio-inoculum for amelioration of soil health and sustainable crop production, Current Research in Microbial Sciences, 7: 100251.
https://doi.org/10.1016/j.crmicr.2024.100251

Schenk P.M., Batool M., Mirzaee H., and Abbott A., 2024, Customized plant growth promotion with soil- and cultivar-compatible microbial biofertilizers, Agronomy, 14(9): 1915.
https://doi.org/10.3390/agronomy14091915

Schnecker J., Baldaszti L., Gündler P., Pleitner M., Sandén T., Simon E., Spiegel F., Spiegel H., Malo C., Zechmeister-Boltenstern S., and Richter A., 2023, Seasonal dynamics of soil microbial growth, respiration, biomass, and carbon use efficiency in temperate soils, Geoderma, 433: 116693.
https://doi.org/10.1016/j.geoderma.2023.116693

Shahwar D., Mushtaq Z., Mushtaq H., Alqarawi A.A., Park Y., Alshahrani T.S., and Faizan S., 2023, Role of microbial inoculants as bio fertilizers for improving crop productivity: a review, Heliyon, 9(6): e16134.
https://doi.org/10.1016/j.heliyon.2023.e16134

Shen W., Hu M., Qian D., Xue H., Gao N., and Lin X., 2021, Microbial deterioration and restoration in greenhouse-based intensive vegetable production systems, Plant and Soil, 463: 1-18.
https://doi.org/10.1007/s11104-021-04933-w

Tao C., Li R., Xiong W., Shen Z., Liu S., Wang B., Ruan Y., Geisen S., Shen Q., and Kowalchuk G.A., 2020, Bio-organic fertilizers stimulate indigenous soil Pseudomonas populations to enhance plant disease suppression, Microbiome, 8: 137.
https://doi.org/10.1186/s40168-020-00892-z

Timofeeva A., Galyamova M., and Sedykh S., 2023, Plant growth-promoting soil bacteria: nitrogen fixation, phosphate solubilization, siderophore production, and other biological activities, Plants, 12(24): 4074.
https://doi.org/10.3390/plants12244074

Trinchera A., Migliore M., Raffa D., Ommeslag S., Debode J., Shanmugam S., Dane S., Babry J., Kivijarvi P., Kristensen H.L., Lepse L., Salo T., Campanelli G., and Willekens K., 2022, Can multi-cropping affect soil microbial stoichiometry and functional diversity, decreasing potential soil-borne pathogens? A study on European organic vegetable cropping systems, Frontiers in Plant Science, 13: 952910.
https://doi.org/10.3389/fpls.2022.952910

Wang J., Liu L., Gao X., Hao J., and Wang M., 2021, Elucidating the effect of biofertilizers on bacterial diversity in maize rhizosphere soil, PLoS ONE, 16(4): e0249834.
https://doi.org/10.1371/journal.pone.0249834

Wang J., Sun L., Sun Y., Yang S., Qin Q., and Xue Y., 2025, Integrated enzyme activities and untargeted metabolome to reveal the mechanism that allow long-term biochar-based fertilizer substitution improves soil quality and maize yield, Environmental Research, 270: 120935.
https://doi.org/10.1016/j.envres.2025.120935

Wang T., Cheng K., Huo X., Meng P., Cai Z., Wang Z., and Zhou J., 2022, Bioorganic fertilizer promotes pakchoi growth and shapes the soil microbial structure, Frontiers in Plant Science, 13: 1040437.
https://doi.org/10.3389/fpls.2022.1040437

Wu J., Shi Z., Zhu J., Cao A., Fang W., Yan D., Wang Q., and Li Y., 2022, Taxonomic response of bacterial and fungal populations to biofertilizers applied to soil or substrate in greenhouse-grown cucumber, Scientific Reports, 12: 18623.
https://doi.org/10.1038/s41598-022-22673-4

Ye L., Zhao X., Bao E., Li J., Zou Z., and Cao K., 2020, Bio-organic fertilizer with reduced rates of chemical fertilization improves soil fertility and enhances tomato yield and quality, Scientific Reports, 10: 177.
https://doi.org/10.1038/s41598-019-56954-2

Zhang L., Jing Y., Chen C., Xiang Y., Rashti M.R., Li Y., Deng Q., and Zhang R., 2021, Effects of biochar application on soil nitrogen transformation, microbial functional genes, enzyme activity, and plant nitrogen uptake: a meta-analysis of field studies, GCB Bioenergy, 13(12): 1859-1873.
https://doi.org/10.1111/gcbb.12898

Zhang Y., Xiao R., Zhao Y., Li T., Cheng H., and Zhang H., 2025, Impact of phosphorus reduction combined with biofertilizer application on soil nutrients and microbial communities in arid oasis agricultural areas, Frontiers in Microbiology, 16: 1606813.
https://doi.org/10.3389/fmicb.2025.1606813

Zhao Y., Lu G., Jin X., Wang Y., Wang K., Zhang H., Yan H., and Zhou X., 2022, Effects of microbial fertilizer on soil fertility and alfalfa rhizosphere microbiota in alpine grassland, Agronomy, 12(7): 1722.
https://doi.org/10.3390/agronomy12071722