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FROM SOIL TO SILK: APPLICATIONS OF BENEFICIAL MICROORGANISMS IN SUSTAINABLE SERICULTURE

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ABSTRACT

Sericulture constitutes a biologically integrated agro-ecosystem in which soil health, plant nutrition, microbial dynamics, and insect physiology are tightly interconnected and collectively determine productivity and silk quality. Increasing reliance on chemical-intensive inputs has raised concerns regarding environmental sustainability, soil degradation, and system resilience. In this context, beneficial microorganisms have emerged as critical biological drivers capable of enhancing nutrient cycling, plant vigor, insect health, and silk production through eco-efficient mechanisms. This review synthesizes recent advances on the functional roles of beneficial microorganisms across the sericultural production continuum, encompassing rhizosphere-mediated nutrient acquisition, microbial regulation of insect digestion and immunity, and microbial contributions to cocoon characteristics and silk quality. Emphasis is placed on mechanistic insights underlying soil–plant–insect interactions and their relevance to sustainable, low-input sericulture systems. By integrating evidence across trophic levels, this review highlights the potential of microbial interventions to improve productivity, stabilize silk quality, and reduce dependency on synthetic inputs, while identifying key challenges for their effective implementation in modern sericulture.

Key words: Sericulture, Microorganisms, Soil fertility, Bacteria, Host plant

Introduction

Sericulture functions as a tightly coupled agro-ecosystem in which plant nutrition, microbial dynamics, and insect health collectively regulate silk yield and quality under diverse production environments. Despite its biological complexity and economic significance, contemporary sericulture systems have increasingly depended on chemical-intensive inputs for host plant nutrition and disease management. Prolonged application of synthetic fertilizers, disinfectants, and prophylactic chemicals has resulted in declining soil fertility, disruption of native microbial communities, and increased susceptibility of rearing systems to biotic and abiotic stresses, raising concerns about long-term sustainability and environmental impact (van der Heijden & Schlaeppi, 2015; Pineda *et al.*, 2013; Shravanilakshmi *et al.*, 2025).

In response, recent research has increasingly focused on eco-efficient, biologically driven production systems that incorporate beneficial microorganisms to restore soil health and enhance host performance. Microbial groups such as nitrogen-fixing bacteria, phosphate-solubilizing microorganisms, mycorrhizal fungi, and endophytes have been reported to improve nutrient availability, stimulate plant growth, and enhance stress tolerance across diverse sericultural host plants, thereby improving leaf biomass and nutritional quality critical for larval development (Shravanilakshmi *et al.*, 2025; Bhuvaneshwari *et al.*, 2025).

Concurrently, advances in insect microbiome research have demonstrated the functional importance of gut microbial communities in silkworm physiology, particularly in nutrient assimilation, immune regulation, and disease resistance. Probiotic microorganisms such as *Lactobacillus*, *Bacillus*, and *Bifidobacterium* have been associated with improved growth performance, enhanced cocoon characteristics, and increased resistance to pathogenic infections, highlighting the potential of microbial modulation in sustainable silkworm rearing (Dutta *et al.,* 2025; Ren *et al.,* 2025; Suraporn *et al.,* 2024). Evidence of microbial transfer from host plant surfaces to insect tissues further underscores the integrative nature of sericultural production systems (Zhao *et al.,* 2024).

The soil–plant–insect continuum provides a conceptual framework for understanding these interactions, emphasizing how soil microbial communities influence plant health and, in turn, shape insect physiology and microbial balance. Such microbially mediated, multi-trophic interactions form the basis for targeted interventions aimed at enhancing plant vigor, insect gut stability, immune competence, and overall productivity while minimizing dependence on synthetic inputs (Shikano *et al.,* 2017; Ngumbi, 2025; Li *et al.,* 2023). This review critically synthesizes recent advances on the application of beneficial microorganisms across host plant cultivation and silkworm rearing systems, with emphasis on sustainability and productivity. The soil–plant–insect–silk continuum provides a conceptual framework for understanding how microbially mediated interactions across trophic levels collectively influence sericultural productivity and silk quality (Fig. 1).

Functional Role of Beneficial Microorganisms in the Sericultural Rhizosphere

Beneficial microorganisms inhabiting the sericultural rhizosphere play a pivotal role in regulating plant health and productivity through direct and indirect functional mechanisms. Plant growth-promoting microorganisms, including free-living rhizobacteria, endophytes, and symbiotic fungi, colonize the root surface and surrounding soil to form dynamic associations that influence plant physiology at multiple levels. These microbial assemblages act as biological interfaces between soil and plant systems, modulating root architecture, hormone signaling, and metabolic activity, thereby enhancing overall plant vigor and resilience (van der Heijden & Schlaeppi, 2015; Shikano *et al.,* 2017). These mechanisms collectively illustrate how rhizosphere microorganisms regulate nutrient acquisition, plant vigor, and stress tolerance in sericultural cropping systems (Fig. 2).

A primary functional contribution of beneficial rhizosphere microorganisms lies in their ability to mediate nutrient acquisition and bioavailability. Microbial processes such as biological nitrogen fixation, phosphate solubilization, siderophore-mediated iron mobilization, and enzymatic mineralization of organic matter enhance nutrient uptake efficiency while maintaining soil fertility. Recent field-based studies demonstrate that microbial enrichment strategies significantly improve soil nutrient status and microbial population dynamics, reinforcing sustainable nutrient cycling and reducing dependence on synthetic fertilizers (Shravanilakshmi *et al.,* 2025; Li *et al.,* 2023). These mechanisms operate not only at the soil–root interface but also influence aboveground plant metabolic profiles, linking belowground microbial activity to system-level productivity.

Beyond nutrient mobilization, beneficial microorganisms contribute to improved plant vigor by enhancing biochemical quality and tolerance to abiotic stresses such as drought, salinity, and nutrient imbalance. Microbial endophytes and rhizosphere-associated fungi can induce systemic tolerance by modulating antioxidant activity, osmolyte accumulation, and secondary metabolite production, resulting in improved leaf nutritional composition and stress resilience. Evidence from recent reviews and experimental studies highlights the capacity of

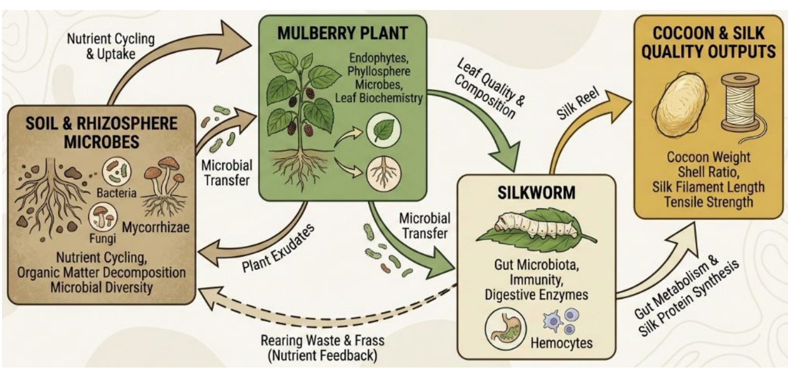

Fig. 1: Conceptual representation of microbially mediated interactions across the soil–plant–insect continuum influencing silkworm health, cocoon traits, and silk quality in sustainable sericulture.

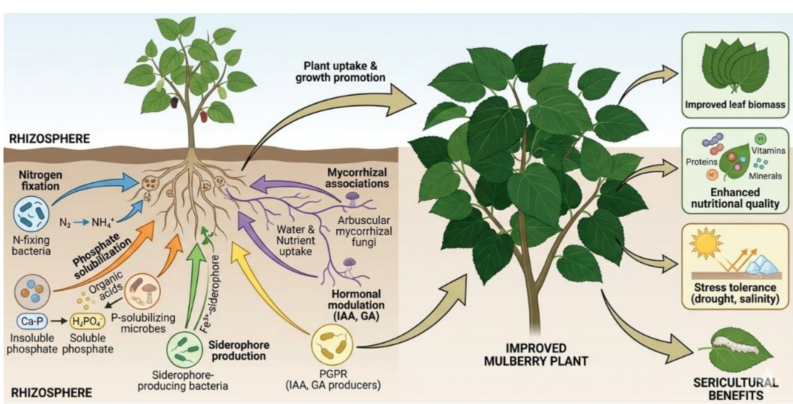

Fig. 2: Functional mechanisms of beneficial rhizosphere microorganisms enhancing nutrient acquisition, plant growth, and stress tolerance in mulberry-based sericulture systems.

beneficial microbial partnerships to stabilize plant performance under variable environmental conditions, thereby supporting consistent biomass production in sericultural landscapes (Bhuvaneshwari *et al.,* 2025; Ngumbi, 2025).

Collectively, the functional integration of beneficial microorganisms into the sericultural rhizosphere offers a viable pathway to reduce external fertilizer dependency while maintaining productivity. By enhancing nutrient use efficiency, improving plant biochemical attributes, and reinforcing stress tolerance, microbial interventions contribute to the development of low-input, eco-efficient sericulture systems. Importantly, these rhizosphere-level processes form the foundational link in the soil–plant–insect continuum, enabling downstream benefits that extend beyond plant health to influence higher trophic interactions and system sustainability (Pineda *et al.,* 2013; Ngumbi, 2025).

Microbial Regulation of Insect Health, Immunity, and Performance

Insect-associated microbial communities, especially those residing in the digestive tract, provide essential physiological functions that extend far beyond nutrient digestion. Gut microbes produce enzymes that support the breakdown of complex dietary components and supply metabolites that enhance host metabolic efficiency and growth performance (Ment & Mishra, 2025; Wang *et al.,* 2024). These microbial contributions are fundamental to nutrient acquisition and can modulate host energy balance, thereby influencing developmental timing and life-history traits.

Microbiota also play a central role in modulating immune responses and resistance to pathogens. Insects exhibit *immune priming*, wherein exposure to beneficial microbes or their molecular patterns enhances baseline immune signalling pathways and antimicrobial peptide expression, enabling more robust responses to subsequent pathogen challenges. Recent research demonstrated that immune priming in the insect gut involves dynamic transcriptomic adjustments that elevate barrier defences and immune effectors, highlighting a mechanistic connection between microbial presence and host immunocompetence (Baur *et al.,* 2025; Li *et al.,* 2023). Additionally, microbial taxa can competitively exclude opportunistic pathogens through nutrient competition and antimicrobial metabolite production, further enhancing host resilience.

Plant-associated microbes acquired during feeding can also modify insect physiology through trophic transfer of microbial signals or metabolites. Cross-compartment interactions between plant microbiomes and insect gut communities influence both digestive and immune system dynamics in herbivorous insects, suggesting that microbe-mediated effects on host health extend beyond gut localization (Zhao *et al.,* 2024; Li *et al.,* 2023). These interactions can enhance tolerance to dietary stressors and improve performance under suboptimal environmental conditions.

At broader ecological scales, intestinal microbiota influence host behavior and environmental adaptability. Microbes can modulate host feeding preferences, sensory perception, and response to environmental stimuli through molecular signaling and metabolic outputs (Wang *et al.,* 2024). These behavioral effects, alongside metabolic and immune interaction mechanisms, underscore the central role of microbiomes in shaping insect health, performance, and ecological fitness across connected biological systems.

Microbial Contributions to Cocoon Characteristics and Silk Quality

Microbial interventions applied during the sericultural production chain have been increasingly linked to improvements in economically relevant cocoon traits. Experimental evidence indicates that dietary and environmental microbial inputs can influence cocoon weight, shell ratio, and filament length by modulating host nutrient assimilation and metabolic efficiency (Ren *et al.,* 2025; Dutta *et al.,* 2025). These improvements are primarily attributed to enhanced digestion of proteins and carbohydrates, resulting in greater availability of amino acids required for silk protein synthesis.

Beyond quantitative yield parameters, microbial influences extend to the biochemical composition of silk proteins. Alterations in gut microbial communities have been shown to affect amino-acid metabolism pathways, including glycine, alanine, and serine fluxes that are critical for fibroin and sericin biosynthesis (Ren *et al.,* 2025; Wang *et al.,* 2024). Such metabolic modulation may indirectly affect molecular alignment and crystallinity of silk fibers, thereby influencing tensile strength and elasticity, key determinants of silk quality in commercial applications.

Recent studies also suggest that microbial exposure contributes to improved fiber integrity and disease resilience, reducing subclinical stress that negatively affects cocoon uniformity and silk reeling performance. Probiotic supplementation has been associated with enhanced resistance to microbial and viral challenges, minimizing physiological disruptions during spinning stages and supporting consistent filament formation (Suraporn *et al.,* 2024; Zhao *et al.,* 2024). These findings highlight the role of microorganisms not merely as growth enhancers, but as stabilizing agents that protect silk quality under variable rearing conditions.

From an economic perspective, microbial-mediated improvements in cocoon and silk traits directly support value-added and sustainable silk production systems. By improving quality parameters without reliance on chemical growth promoters, microbial interventions align with low-input and organic sericulture frameworks while maintaining market-relevant fiber standards (Ngumbi, 2025; Ment & Mishra, 2025). Collectively, these studies position beneficial microorganisms as functional tools for enhancing both biological efficiency and economic returns in sustainable sericulture.

Future Perspectives

Despite significant progress, the successful translation of microbial research into field-scale sericulture remains constrained by strain specificity, ecological context, and variability in host–microbe compatibility, underscoring the need for rigorous functional validation beyond taxonomic identification (van der Heijden & Schlaeppi, 2015; Ment & Mishra, 2025). Increasing evidence indicates that plant-, soil-, and insect-associated microbiomes operate as dynamically interconnected systems, where cross-compartment microbial exchange and signaling collectively influence host performance and resilience (Li *et al.*, 2023; Ngumbi, 2025). Consequently, future research must adopt systems-level approaches to design microbial consortia capable of functioning synergistically across biological interfaces. From a translational perspective, improving formulation stability, delivery strategies, and environmental persistence is essential to ensure consistent microbial efficacy under variable rearing conditions (Pineda *et al.*, 2013; Ngumbi, 2025). Advancing these integrative and mechanism-driven strategies will be critical for embedding beneficial microorganisms into resilient, low-input sericulture systems that sustain productivity and silk quality under changing agro-ecological scenarios.

Conclusion

Beneficial microorganisms have emerged as indispensable components of sustainable sericulture, functioning across interconnected soil, plant, and insect systems to regulate productivity, resilience, and silk quality. The evidence synthesized in this review demonstrates that microbial-mediated processes enhance nutrient use efficiency, stabilize host physiological functions, and support economically important cocoon and silk traits without reliance on chemical-intensive inputs. By operating along the soil–plant–insect continuum, microbial interventions provide system-level benefits that extend beyond isolated growth responses, reinforcing ecological balance and production stability. Collectively, these findings underscore a paradigm shift toward biologically integrated sericulture, where microbial ecology forms the foundation for resilient, low-input, and value-driven silk production systems capable of meeting future environmental and economic challenges.

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