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Nutrient use efficiency in mulberry: Advances in nano-fertilizers, biofertilizers, and agronomic practices

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Abstract
Nutrient use efficiency (NUE) in mulberry (*Morus* spp.) has emerged as a critical determinant of sericulture sustainability, influencing both leaf nutritional quality and cocoon productivity. Conventional fertilizer regimes, while productive in the short term, are increasingly constrained by nutrient imbalances, soil degradation, and environmental losses. Recent innovations provide a multi-dimensional framework for improving NUE in mulberry systems. Nano-fertilizers enable slow release and targeted nutrient delivery, reducing leaching and synchronizing supply with plant demand. Biofertilizers and microbial inoculants improve nutrient solubilization, uptake, and stress tolerance, offering biological routes to reduce chemical dependence. Integrated nutrient management (INM) approaches further combine conventional fertilizers, organic manures, and biofertilizers to balance productivity with soil health. Agronomic interventions—including optimized irrigation and fertigation, strategic pruning and harvesting, and soil amendments such as compost, biochar, and recycled sericulture waste—create synergies that enhance nutrient availability and leaf quality. Future prospects point toward convergence of nano-technologies, microbial consortia, and precision agronomy, supported by robust field trials, standardized regulatory pathways, and farmer-participatory models. Together, these approaches can significantly raise NUE, improve silk yield and quality, and lower the environmental footprint of sericulture.

Keywords: Nutrient use efficiency, nano-fertilizers, biofertilizers, integrated nutrient management, sericulture sustainability

1. Introduction

Mulberry (*Morus* spp.) is the principal feed crop for *Bombyx mori* and the backbone of sericulture worldwide. Leaf chemical composition - protein, carbohydrates, vitamins, minerals and secondary metabolites directly determines silkworm growth, cocoon yield, and silk quality. Recent analyses show wide variation in leaf nutrient and phytochemical profiles across mulberry species and cultivars, which in turn affects larval performance and product value [1, 2].

Despite its economic importance, mulberry cultivation often relies on conventional fertilizer regimes that deliver nutrients inefficiently. Low nutrient use efficiency (NUE) raises production costs and causes environmental losses through leaching and volatilization. These problems reduce leaf quality over time and undermine sustainable sericulture, especially where soils are degraded or water is limiting (reviews and field studies across Asia show persistent NUE gaps) [3].

New approaches aim to close that NUE gap while improving leaf nutritional quality. Two promising routes are nano-fertilizers, which can provide controlled or targeted nutrient release, and biologicals such as plant growth promoting microbes that enhance uptake and stress tolerance. Early mulberry studies report improved leaf nutrient content, growth and even downstream larval and cocoon traits following nano-nitrogen applications or bioinoculants, although results vary by formulation, dose, and local [4, 5].

Improving nutrient use efficiency in mulberry is not only about raising leaf yield but also about maintaining soil health and reducing input costs for sericulture farmers. A balanced perspective that connects leaf nutrient quality with innovative inputs like nano-fertilizers and biofertilizers, along with supportive agronomic practices, is needed to chart a sustainable path forward. This review brings together recent insights on how these approaches can enhance mulberry productivity, strengthen cocoon yield and quality, and reduce the environmental footprint of sericulture systems.

2. Nutrient Use Efficiency in Mulberry: Current Status and Challenges

Mulberry's rapid, repeated harvesting cycles place an exceptionally heavy demand on soil fertility. Traditional recommendations commonly call for NPK inputs of around 350-140-140 kg ha^{-1} per year, supplemented by large quantities of farm yard manure (FYM), often as much as 20 t ha^{-1} annually, especially in irrigated gardens to sustain continuous high foliar yield. Over time, such heavy nutrient extraction without balanced replenishment has led to declining soil pH, salinity concerns, and reductions in organic carbon and essential nutrient levels across diverse mulberry-growing zones [6].

Furthermore, region-specific soil investigations (for example, in West Bengal) reveal that mulberry soils are predominantly acidic, with widespread deficiencies in nutrients such as sulphur, potassium, and boron, highlighting the prevalence of suboptimal nutrient management practices among many cultivators [7]. These findings underscore that reliance on untargeted fertilizer application or no fertilizer planning at all is still common, resulting in low NUE, reduced leaf quality, and weaker cocoon productivity.

Even when fertilizers are applied, they're often unbalanced or heavily skewed toward macronutrients, ignoring important secondary and micronutrient needs. For instance, trials comparing conventional straight fertilizers (urea, Diammonium phosphate (DAP), Muriate of potash (MOP)) with balanced applications including bentonite sulphur and zinc sulphate show that balanced formulations significantly boosted leaf yield, chlorophyll, soluble protein, and sugar content, while also enhancing indicators of NUE such as agronomic use efficiency (AUE) and partial factor productivity (PFP) [8].

Collectively, these patterns point to critical challenges: many mulberry systems still use outdated or blanket fertilizer regimes; soils are being depleted of essential nutrients and organic matter; and NUE remains low. Unless these gaps are addressed via diagnostics like soil testing and adopting balanced, site-specific nutrient programs, mulberry cultivation may struggle with sustainability, escalating costs, and long-term degradation of productivity and silk quality. To address these challenges, a structured decision framework for nutrient management in mulberry is outlined in Figure 1. This flowchart links soil diagnostic results to the choice of balanced chemical inputs, nano-fertilizers, biofertilizers, integrated nutrient management (INM), and organic amendments. A summary of the major strategies currently explored to enhance nutrient use efficiency in mulberry is presented in Table 1.

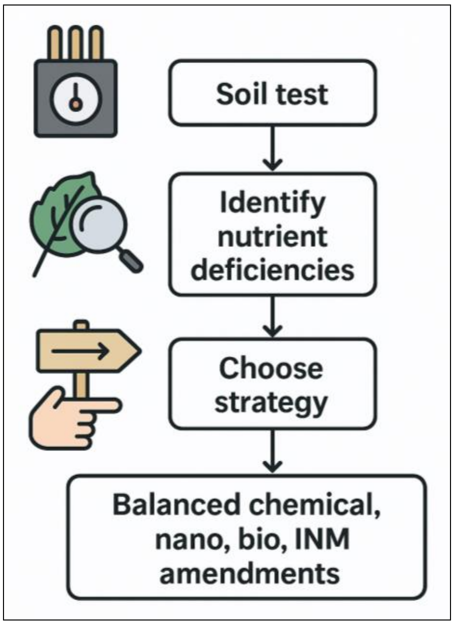

Fig 1: Decision flow for nutrient management in mulberry, linking soil test results to chemical, nano, bio, INM, or organic options (Source: Author's own illustration).

Table 1: Strategies for Improving Nutrient Use Efficiency (NUE) in Mulberry (*Morus* spp.)

Strategy	Key Inputs/Practices	MainBenefits	Limitations/Concerns	References
Conventional Fertilizers	NPK (urea, DAP, basal/top dressing)	Rapid nutrient availability, supports high leaf yield	Low NUE due to leaching and volatilization; soil acidification; long-term degradation	[6, 7, 8]
Organic Amendments	Farmyard manure (FYM), compost, seriwaste recycling	Improves soil organic carbon, microbial activity, and leaf quality	Nutrient release slower than chemical fertilizers; bulky handling required	[9, 10, 11]
Biochar	Mulberry stalk biochar, shoot biochar blends with FYM	Enhances soil fertility, water retention, and NUE; sequesters Carbon	Effect varies with feedstock, pyrolysis, and soil type	[12, 13, 14, 15]
Biofertilizers & Microbial Inoculants	N-fixers, P-solubilizers, PGPR, mycorrhiza, microbial consortia	Increase nutrient availability, enhance stress tolerance, improve leaf N & protein	Inconsistent field performance; formulation and shelf-life challenges	[5, 10, 16, 17, 18]
Nanofertilizers	Nano-N, nano-P, slow/controlled release nano-chelates	Higher NUE via targeted release, reduced losses, lower application rates	High production cost; biosafety and regulation still under debate	[3, 4, 19, 20]
Integrated Nutrient Management (INM)	Balanced mix of chemical, organic, nano, and biofertilizer inputs	Sustains yield, improves soil health, reduces environmental footprint	Requires careful site-specific management and monitoring	[8, 11, 21]

3. Emerging Approaches to Enhance NUE in Mulberry

Enhancing nutrient use efficiency (NUE) in mulberry cultivation is pivotal for sustainable sericulture. Traditional fertilization practices often lead to nutrient imbalances and environmental concerns. Emerging approaches, including nano-fertilizers, biofertilizers, and integrated nutrient management (INM), offer promising solutions to address these challenges.

3.1 Nano-fertilizers: Slow Release and Targeted Delivery

Nano-fertilizers are engineered to release nutrients gradually, ensuring a steady supply to plants and minimizing nutrient losses through leaching and volatilization. These fertilizers offer controlled and sustained nutrient release, promoting efficient nutrient uptake and utilization. Studies have demonstrated that nano-fertilizers can significantly improve NUE in various crops, including mulberry. For instance, a study by Haydar *et al*. (2024) reported that nano-fertilizers enhanced nutrient uptake and utilization efficiency in mulberry, leading to increased leaf yield and quality [22]. Furthermore, nano-fertilizers can be tailored to deliver specific nutrients at different growth stages of mulberry, optimizing nutrient availability and uptake. This targeted delivery system aligns nutrient supply with plant demand, enhancing NUE and promoting sustainable mulberry production [23].

3.2 Biofertilizers and Microbial Inoculants: Enhancing Nutrient Availability

Biofertilizers, including nitrogen-fixing bacteria, phosphorus-solubilizing microorganisms, and mycorrhizal fungi, play a crucial role in enhancing nutrient availability and uptake in mulberry plants. These microorganisms improve soil fertility by converting unavailable nutrients into forms accessible to plants. A review by Kalayu (2019) emphasized the importance of phosphate-solubilizing microorganisms in agriculture, noting their role in enhancing nutrient availability and promoting sustainable farming practices [16]. In mulberry cultivation, the application of biofertilizers has been shown to improve leaf yield and quality. For example, a study by Pavankumar *et al*. (2024) found that inoculation with nitrogen-fixing and phosphorus-solubilizing bacteria enhanced mulberry growth and leaf nutrient content, thereby improving silkworm productivity [10]. Additionally, biofertilizers can enhance plant resistance to environmental stresses and diseases, further contributing to improved NUE and sustainable mulberry production [24]. Table 2 compiles key studies on biofertilizers and microbial inoculants in mulberry, highlighting their impacts on yield, leaf quality, and nutrient use efficiency.

Table 2: Biofertilizers and microbial inoculants in mulberry cultivation: effects on yield, quality, and NUE

Microbe type	Function	Effects on mulberry leaf yield/quality/NUE	References
N-fixing bacteria (e.g., Azotobacter, Azospirillum)	Fix atmospheric N, improve root growth and nutrient uptake	Increased leaf yield, higher leaf nitrogen content, improved silkworm growth and cocoon traits	[10, 16]
P-solubilizing bacteria (PSB, e.g., Bacillus, Pseudomonas)	Solubilize unavailable soil P, secrete organic acids and enzymes	Enhanced P availability, improved leaf phosphorus levels, increased nutrient use efficiency	[16, 24]
Microbial consortia (N-fixers + PSB + beneficial rhizobacteria)	Synergistic nutrient mobilization, growth promotion	Greater leaf biomass, balanced nutrient profile, higher NUE compared to single inoculants	[10, 17]
Endophytic and rhizospheric fungi (e.g., Trichoderma, Arbuscular Mycorrhizal Fungi (AMF))	Enhance nutrient uptake, root colonization, stress tolerance	Improved soil fertility, better nutrient assimilation, higher leaf protein and chlorophyll	[18, 25]
Plant Growth-Promoting Rhizobacteria (PGPR, general)	Produce phytohormones, improve nutrient uptake, suppress pathogens	Improved soil microbial activity, enhanced leaf yield and quality, reduced fertilizer requirement	[17, 25]

3.3 Integrated Nutrient Management (INM): Combining Conventional, Nano, and Organic Inputs

Integrated Nutrient Management (INM) involves the judicious use of chemical fertilizers, organic manures, and biofertilizers to optimize nutrient availability and enhance soil health. This holistic approach aims to achieve sustainable mulberry production by balancing nutrient inputs and minimizing environmental impacts [21]. A study by Rakshitha *et al*. (2025) assessed the influence of different INM practices on the biochemical parameters of tree mulberry, indicating that combining chemical fertilizers with organic inputs and biofertilizers can improve leaf quality and yield [11]. Moreover, INM practices can enhance soil microbial diversity and activity, leading to improved nutrient cycling and availability. This integrated approach not only boosts NUE but also promotes long-term soil fertility and sustainability in mulberry cultivation [26]. To highlight the contrast between conventional fertilization and innovative nano/bio inputs, Figure 2 illustrates the major nutrient loss pathways and the mechanisms through which advanced inputs improve nutrient use efficiency.

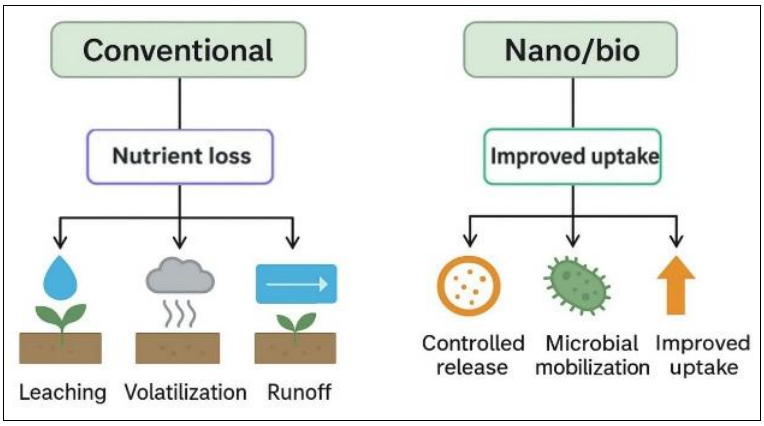

Fig 2: Nutrient loss pathways under conventional fertilization and improved uptake with nano/bio inputs (Source: Author's own illustration).

4. Agronomic Interventions Supporting NUE

4.1 Irrigation and fertigation

Efficient water delivery strongly conditions how much of the applied N, P, and K a mulberry plant actually takes up. Moving from surface irrigation to drip systems with fertigation typically raises water-use efficiency (WUE) and nutrient-use efficiency (NUE) by reducing leaching and keeping nutrients in the active root zone. In a field study on mature S-1635 mulberry, a low-cost drip-fertigation setup delivering 75-100% of the recommended NPK outperformed surface irrigation at 100% dose, increasing leaf yield and quality while cutting water use and boosting WUE and NUE [27]. Under water-saving regimes, genotype also matters: a two-year trial in North China showed that deficit irrigation combined with a drought-tolerant cultivar maintained higher leaf protein and yield, indicating scope to pair irrigation scheduling with variety choice to protect leaf quality for rearing [28]. Reviews of protected/controlled cultivation add that hydroponic or vertical systems can couple precise irrigation with soluble nutrition to further limit losses and raise productivity per unit input, though adoption costs and management skill are limiting factors [29].

Taken together, the practical levers are: drip over surface irrigation; split applications via fertigation aligned with crop evapotranspiration; and cultivar selection under limited irrigation. These steps reduce N loss pathways (runoff, deep percolation, volatilization) and keep soluble N and K available during rapid canopy expansion, which directly improves leaf protein and sugars for silkworm diets [27, 28].

Key implications for NUE: Schedule irrigation to ET and deliver N and K through the lines in small, frequent doses; consider moderate deficit irrigation with tolerant genotypes to sustain leaf protein while curbing losses; and, where feasible, use protected/soilless systems to tighten the water-nutrient loop [27, 28, 29].

4.2 Pruning and harvesting practices

Pruning height and frequency govern shoot flush, leaf area development, and the timing of nutrient demand. Experiments with V-1 mulberry found that pruning at around 150 cm produced more shoots, more leaves, and higher per-plant leaf yield at 60 days after pruning than lower cuts, implying a better balance between vegetative vigor and harvestable biomass [30]. Seasonal scheduling matters as well: adjusting pruning and rearing dates by about two weeks in the lower Gangetic plain significantly increased leaf yield and improved leaf moisture, soluble proteins, and sugars, aligning peak leaf quality with silkworm demand[31]. Longer-term spacing and “small-tree” training studies also show that coordinated pruning and harvest intervals of roughly 50-70 days stabilize multi-year leaf yield, which helps synchronize fertilizer supply with actual uptake, reducing waste [32].

In practice, a slightly higher stump and disciplined harvest interval can concentrate growth into well-lit, rapidly expanding shoots with high specific leaf weight and protein. That makes fertilizer timing more predictable, short pulses of N and K can be targeted to post-pruning regrowth and pre-harvest windows when uptake is strongest [30, 31, 32].

4.3 Soil amendments (compost, biochar, sericulture-waste recycling)

Organic amendments improve NUE by increasing soil cation-exchange capacity, water holding, and biological activity, which all dampen nutrient losses and increase synchronized supply. Multi-season field work shows that composted sericulture waste (“seriwaste”) increases mulberry leaf yield and quality, improves soil organic carbon, and raises available NPK while also enhancing cocoon performance, an integrated recycling pathway that closes nutrient loops within the farm [9]. Biochar made from mulberry residues or farm by-products has also performed well: field trials with mulberry-stalk biochar plus farmyard manure (FYM) improved soil pH, organic carbon, CEC, and available NPK, and raised leaf yield and nutrient uptake relative to standard practice [12, 13, 14]. These effects align with broader biochar literature showing reduced N leaching, better water retention, and a more active microbial community that supports mineralization and uptake [15].

For day-to-day management, the most consistently useful combinations in mulberry gardens are: (i) 5-10 t ha^{-1} mulberry-stalk biochar co-applied with ~10 t ha^{-1} FYM to raise base fertility and buffer pH, (ii) periodic top-ups with seriwaste compost to recycle in-house nutrients, and (iii) smaller soluble N/K fertigation pulses layered on top to meet peak demand after pruning. This “organic backbone + precise top-dressing” pattern is where farms report the best mix of yield, leaf quality, and nutrient efficiency [9, 13, 14, 15].

5. Future Prospects

5.1 Nano-technology and precision nutrient delivery

Nano-enabled fertilizers and other smart fertilizer technologies offer a clear route to raise NUE by controlling release rates and targeting nutrient delivery to the rhizosphere. Nanoparticles, nano-coatings and controlled-release matrices can reduce losses from leaching and volatilization, and they can synchronize supply with crop demand using smaller, more frequent doses. Recent reviews synthesize design principles, agronomic benefits and environmental risks, and show consistent yield and NUE gains across crops when nano-formulations are properly matched to soil and crop physiology [20, 33]. At the same time, the literature flags Knowledge gaps: long-term soil fate, interactions with soil biota, standardization of dose metrics, and crop-specific efficacy trials are needed before wide adoption in mulberry.

5.2 Rational design and deployment of microbial consortia

Single-strain biofertilizers work in some contexts, but engineered or well-selected microbial consortia often give broader and more reliable benefits. Consortia can combine nitrogen fixation, phosphorus solubilization, hormone production and biocontrol functions. Reviews and experimental studies show consortia improve nutrient uptake, stress tolerance and crop resilience more consistently than single strains, provided strains are compatible and adapted to local soils [17, 18, 25]. Future work should prioritize formulation stability, shelf life, field validation across regions, and mechanistic studies on how consortia interact with native microbiomes in mulberry rhizospheres.

5.3 Integrated smart systems: combining nano, bio and precision agronomy

The greatest gains in NUE will likely come from integration: nano-formulations for controlled release, microbial consortia for enhanced uptake and cycling, and precision agronomy tools (soil sensors, fertigation, remote sensing) to match supply with demand in space and time. Reviews of smart fertilizers and precision nutrient management argue that the synergy of these approaches reduces inputs while maintaining or increasing yield and quality [19, 34]. For mulberry, this means designing field trials that combine foliar nano-applications, root-applied bioinoculants, and drip fertigation controlled by simple soil moisture/N sensors. Those trials should measure leaf biochemical markers that predict silkworm performance, not just biomass.

5.4 Environmental safety, standardization and regulatory pathways

Before broad deployment, nano- and microbial products need standardized testing for environmental fate, non-target effects, and human safety. Reviews repeatedly call for harmonized protocols for ecotoxicology, dose metrics (what “1 kg” of nano-

N actually means), and monitoring frameworks [33, 34]. Recent biochar studies further suggest that material heterogeneity complicates risk prediction, since feedstock type and pyrolysis temperature directly influence nutrient release patterns and persistence in soils [12, 13]. Similarly, microbial consortia pose challenges in standardization, as synergistic effects vary with host plant genotype and local soil microbiomes, making reproducibility a key hurdle [17, 18]. Policy adoption will also hinge on extension systems and cost-benefit clarity for smallholders. Targeted pilot programs that couple technical validation with farmer participatory trials will accelerate uptake while ensuring regulatory oversight.

5.5 Research priorities and field trial design for mulberry

To move from promise to practice, research should prioritize: (1) multi-season, multi-site trials that report both leaf biochemical quality and cocoon metrics; (2) factorial trials combining nano-inputs, microbial consortia and fertigation timing; (3) dose-response and residual monitoring for soils and beneficial microbes; and (4) economic and life-cycle assessments that explicitly compare conventional, INM and smart-input systems. Trials should also synchronize experimental treatments with standard pruning and harvesting schedules used by farmers so that nutrient supply is tested under real operational timing and the measured leaf chemistry matches the actual feed offered to silkworms [31, 32]. In addition, when testing biologicals, trial designs must include consortium stability and compatibility checks across seasons to capture carryover or antagonistic effects on native rhizosphere communities [17, 18]. Reviews and meta-analyses in the broader crop literature offer trial templates and metrics that can be directly adapted to mulberry research programs [17, 20].

6. Conclusion

Mulberry cultivation stands at the intersection of agricultural innovation and ecological necessity. This review shows that advancing nutrient use efficiency requires both technological inputs and context-specific agronomic strategies. Nano-fertilizers and biofertilizers provide novel avenues for targeted nutrient supply and enhanced uptake, while integrated nutrient management secures long-term soil fertility. Complementary practices such as drip fertigation, pruning optimization, and organic recycling further improve synchronization between nutrient availability and crop demand. The way forward lies in integration: combining smart nutrient inputs with precision agronomy and farmer-centered practices. If these approaches are systematically validated through rigorous field trials and adopted within enabling policy frameworks, they can deliver higher-quality mulberry leaves, more resilient sericulture systems, and a reduced environmental burden. Ultimately, strengthening NUE in mulberry is key not just for sustaining cocoon yields but also for safeguarding the long-term ecological balance and livelihood security of sericulture.

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