**Review Article**

**“Emerging Nutritional and Climate-Resilient Strategies in Mulberry for Enhanced Cocoon Quality in Sericulture”**

**Abstract**

Sericulture relies fundamentally on the nutritional quality of mulberry (*Morus* spp.) leaves, which serve as the exclusive feed for the silkworm, *Bombyx mori* L. In recent years, efforts have intensified to improve cocoon yield and silk quality through strategic nutritional enrichment of mulberry foliage and adoption of climate-resilient cultivation practices. This review outlines how the integration of soil and foliar nutrient supplementation particularly with elements like nitrogen, zinc, and iron alongside organic amendments and microbial inoculants such as plant growth-promoting rhizobacteria (PGPR) and mycorrhizal fungi, can significantly improve leaf quality. Enhanced leaf nutrition, in turn, positively influences important cocoon characteristics, including larval growth, cocoon weight, shell percentage, filament length, and feed utilization efficiency. Additionally, cultivation techniques tailored to mitigate climatic stresses, such as the use of drought-tolerant mulberry genotypes, mulching, and efficient irrigation systems, contribute to maintaining consistent leaf yield and quality. By combining targeted nutrient strategies with climate-smart agronomic practices, sericulture can achieve higher productivity and improved cocoon traits in an environmentally sustainable manner.

**Keywords**: Mulberry nutrition; *Bombyx mori*; Cocoon quality; Sustainable sericulture; Climate-resilient agronomy, PGPR, Mycorrhiza, Micronutrient supplementation, Feed conversion efficiency, Drought-tolerant mulberry varieties.

**Introduction**

The rearing success of the silkworm (*Bombyx mori* L.) is fundamentally dependent on the quality of mulberry (*Morus* spp.) leaves, which serve as the exclusive nutritional source throughout its larval life cycle. The biochemical composition of mulberry foliage especially its protein, carbohydrate, moisture content, and micronutrient levels plays a pivotal role in determining larval development, silk gland function, and ultimately cocoon yield and filament quality (Dandin et al., 2003; Sharma & Ananthanarayana, 2012; Datta, 2000; Bongale et al., 1997).

Traditionally, sericulture practices have prioritized maximizing mulberry leaf biomass. However, recent shifts in research and field application emphasize quality overquantity, recognizing that nutrient-rich, physiologically balanced foliage is crucial for improving feed conversion efficiency, cocoon weight, and shell percentage. Field-level challenges such as soil nutrient depletion, climatic variability, and unbalanced fertilization have made it increasingly difficult to maintain consistent leaf quality (Ramesh et al., 2011; Sannappa & Mallikarjuna, 2009).

To address these limitations, innovative approaches focusing on nutritional enhancement and climate-resilient agronomic practices are gaining ground. Nutrient enrichment using both chemical and organic sources, along with microbial consortia like Plant Growth-Promoting Rhizobacteria (PGPR) and arbuscular mycorrhizal fungi (AMF), has been shown to improve mulberry physiology and increase the bioavailability of critical nutrients in the leaves (Rani et al., 2018; Jaiswal et al., 2022). These interventions have demonstrated significant improvements in silkworm health and cocoon traits under both laboratory and field conditions.

Parallelly, climate-adaptive strategies, including the adoption of drought-tolerant mulberry genotypes, mulching, intercropping, and water-conserving irrigation systems, are being explored to stabilize leaf yield and quality in regions facing heat stress, erratic rainfall, and water scarcity (Rahmathulla, 2012; Sharma & Ananthanarayana, 2012). Such techniques not only sustain plant growth under adverse environmental conditions but also support year-round silkworm rearing with minimal ecological impact. Additionally, fortified feeding strategies such as the use of fermented leaves or supplements enriched with amino acids, vitamins, and microbial proteins have been reported to enhance silk gland development and filament synthesis, further contributing to cocoon productivity (Kavitha et al., 2014; Mathur et al., 2003).This review synthesizes emerging knowledge on the integration of nutritional and climate-resilient strategies in mulberry cultivation. It highlights their role in enhancing the biological efficiency of *Bombyx mori*, improving cocoon parameters, and promoting sustainable sericulture. It also outlines practical insights for field-level adoption and future research priorities for eco-friendly cocoon yield enhancement.

2. Nutritional Composition and Quality of Mulberry Leaves

The quality and nutritive value of mulberry (*Morus* spp.) leaves are fundamental to the success of silkworm rearing. Various physiological, biochemical, and morphological characteristics of mulberry influence the feeding behavior, digestion efficiency, and silk-producing ability of *Bombyx mori*. The nutritional profile of mulberry is not static, it varies with cultivar type, plant age, season, agronomic practices, and soil fertility (Bongale et al., 1997; Sengupta et al., 1992).

Mulberry leaves are rich in essential nutrients such as proteins, carbohydrates, minerals, vitamins, and secondary metabolites. These nutrients influence several biological traits in silkworms, including larval weight, cocoon shell percentage, and silk filament length (Ramesh et al., 2011; Lakshmi & Ramesh, 2016).). Among the different mulberry varieties, genotypes such as *V1*, *S36*, *Thailand Male*, and *M5* are known for their superior nutritional traits, especially in terms of high protein and moisture content (Datta, 2000; Bongale et al., 1991).

2.1. Macronutrient Profile: Proteins, Carbohydrates, and Moisture

Soluble proteins and reducing sugars are the most critical leaf constituents influencing larval development. High protein content in leaves supports silk gland growth, while sugars provide the metabolic energy required for feeding and spinning (Mathur et al., 2003). The protein-to-carbohydrate ratio plays a crucial role in determining food conversion efficiency and silk output.

2.2. Micronutrients and Minerals in Leaf Physiology

Moisture content contributes significantly to the palatability and digestibility of leaves. Young and tender leaves generally have higher moisture, making them more suitable for early instar larvae. On the other hand, high crude fiber content in mature or coarse leaves reduces digestibility, affecting cocoon production adversely (Koul and Bhagat, 1994).

2.3. Influence of Leaf Maturity and Seasonal Variability

Mulberry leaves supply essential minerals such as calcium (Ca), potassium (K), magnesium (Mg), and trace elements like zinc (Zn) and iron (Fe), which are important for various enzymatic and metabolic activities in silkworms. These nutrients contribute to silk protein synthesis, immune functions, and overall larval vigor (Sannappa and Mallikarjuna, 2009).

2.4. Genotypic Variation in Nutritional Value

The stage of leaf maturity also affects nutrient content. Generally, medium-matured leaves (5th or 6th leaf from the apex) are nutritionally optimal, containing a balanced level of protein, sugars, and minerals (Narayanan et al., 2006). Over-aged leaves may accumulate more lignin and fiber, which can hinder digestion and reduce cocoon weight.

2.5. Seasonal Influence

Leaf quality is significantly affected by seasonal changes. During the monsoon and cooler months, mulberry tends to produce nutrient-rich foliage due to better soil moisture and lower evapotranspiration. In contrast, summer leaves often show reduced chlorophyll, moisture, and protein content due to heat stress (Rahmathulla, 2012).

Overall, the nutritional composition of mulberry leaves is a key determinant of silk productivity. Selecting high-yielding and nutritionally rich genotypes, along with appropriate cultivation and harvesting practices, can significantly improve cocoon yield and silk quality.

3. Nutritional Strategies to Enhance Cocoon Traits in Bombyx mori

Improving the nutritional quality of mulberry (Morus spp.) leaves is a critical frontier in sustainable sericulture. Since silkworms (*Bombyx mori* L.) derive their entire diet from mulberry foliage, the nutritional profile of the leaves directly impacts larval development, cocoon quality, and silk yield. Biofortification refers to the enhancement of the nutritional content of crops via agronomic practices, selective breeding, organic enrichment, or biological interventions such as microbial inoculation. In mulberry, biofortification strategies are increasingly recognized as a sustainable means to improve leaf protein, micronutrient density, and digestibility without relying on synthetic chemical inputs.

**3.1. Conventional Breeding for Nutrient-Rich Mulberry Genotypes**

Traditional breeding programs have made significant strides in developing nutrient-rich mulberry cultivars. Varieties such as V1, S36, and G4 have consistently demonstrated higher crude protein, moisture content, and soluble sugar levels compared to conventional types like Mysore local or Berhampore (Ramesh et al., 2011; Bongale et al., 1997). These high-yielding genotypes not only support better larval weight gain and survival but also contribute to an improved cocoon shell ratio and filament length (Dandin et al., 2003). Breeding efforts now increasingly focus on integrating multi-trait selection, including disease resistance, leaf yield, and nutrient bioavailability, to meet the dual goals of sustainability and productivity (Koul & Dhaliwal, 2019).

**3.2. Micronutrient Supplementation and Fertilizer Management**

Agronomic biofortification through foliar and soil application of micronutrients—particularly zinc (Zn), iron (Fe), boron (B), and magnesium (Mg)—has proven effective in enhancing mulberry leaf quality. Zinc application, for instance, has been reported to enhance photosynthetic efficiency, protein synthesis, and antioxidative enzyme activities in mulberry (Sarkar et al., 2017). Similarly, iron is essential for chlorophyll formation and energy metabolism, and its supplementation has been linked with increased leaf biomass and nitrogen assimilation (Sannappa & Mallikarjuna, 2009). The synergistic application of Zn, Fe, and Mn significantly improves silk gland growth in silkworms and enhances cocoon parameters (Bindroo & Roy, 2015). Recent studies emphasize that optimal micronutrient application schedules can improve leaf protein, moisture retention, and palatability, ultimately boosting larval development and silk quality (Lakshmi & Ramesh, 2016).

**3.3. Organic Amendments and Integrated Nutrient Management (INM)**

Organic matter amendments such as farmyard manure (FYM), green manure, vermicompost, and enriched composts provide essential macro- and micronutrients, improve soil microbial diversity, and enhance the bioavailability of nutrients in mulberry foliage. Kumar et al. (2015) demonstrated that long-term application of compost improved leaf nitrogen and phosphorus levels while reducing the need for chemical fertilizers. Moreover, organic inputs contribute to improved soil structure, water-holding capacity, and cation exchange, all of which indirectly benefit leaf nutritional quality (Sharma & Ananthanarayana, 2012). Integrated nutrient management (INM) a combination of organic and inorganic fertilizers offers a balanced approach for sustained productivity and nutrient-rich foliage under varying agro-climatic conditions.

**3.4 Plant Growth-Promoting Rhizobacteria (PGPR)**

Biofertilization using beneficial microbes like *Azospirillum*, *Azotobacter*, *Bacillus subtilis*, and *Pseudomonas fluorescens* is an emerging trend in mulberry biofortification. PGPR enhances nitrogen fixation, phosphate solubilization, and phytohormone production, thereby increasing plant vigor and leaf nutritional content (Rani et al., 2018). PGPR-treated mulberry plots have shown significant increases in leaf protein and chlorophyll content, leading to better cocoon quality and larval survival rates (Sarkar et al., 2017). Co-inoculation with arbuscular mycorrhizal fungi (AMF) further improves root nutrient uptake, drought resistance, and overall plant health (Manjula et al., 2017). This biological approach is especially effective in low-input farming systems and degraded soils.

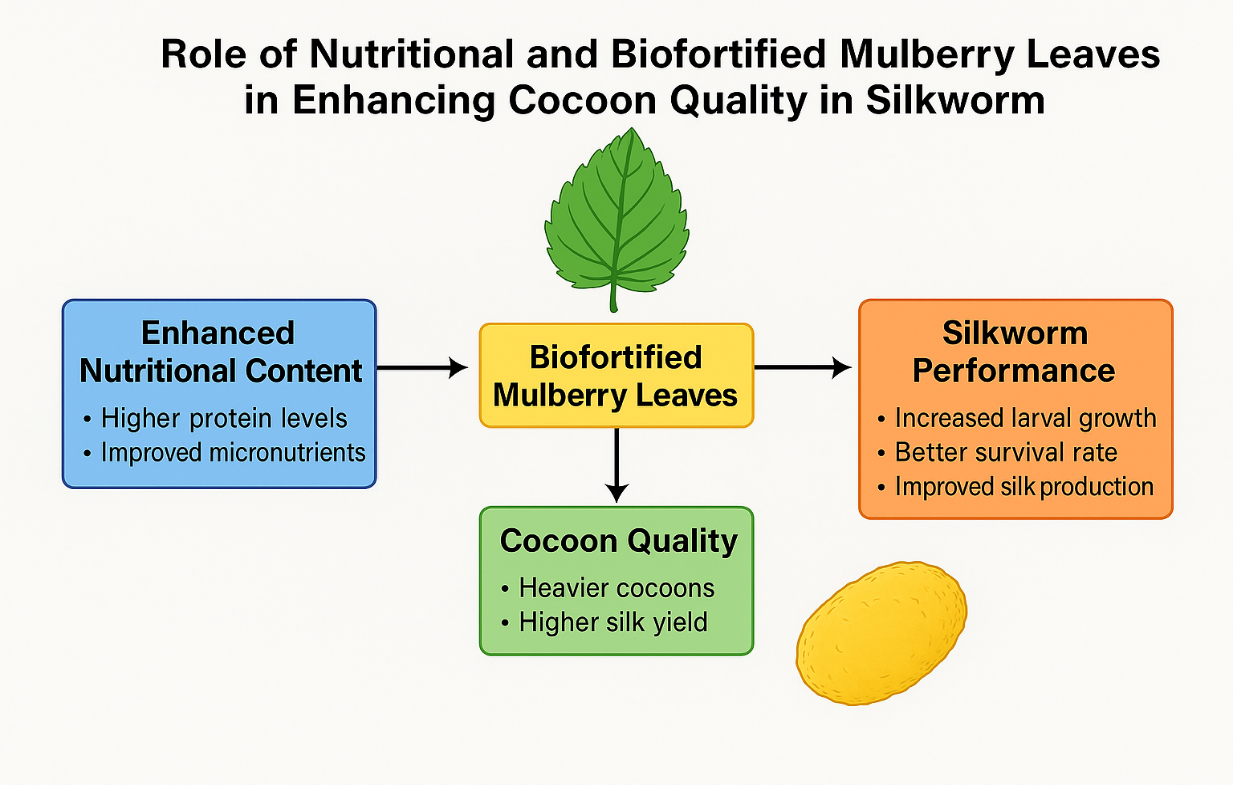
**3.5 Fermented and Fortified Leaf Supplements**

Innovative strategies such as leaf fermentation and post-harvest nutrient fortification are gaining attention for their ability to directly enhance silkworm nutrition. Fermented mulberry leaves using microbial cultures, yeast extracts, or amino acid solutions increase digestibility, improve gut health in larvae, and stimulate silk gland development (Kavitha et al., 2014; Boraiah et al., 2015). Studies have shown that Spirulina and Chlorella-based mulberry leaf enrichments enhance larval metabolism and silk protein synthesis, especially during late instar stages (Lakshmi et al., 2018). These approaches offer flexibility for targeted nutritional interventions, particularly in controlled rearing conditions or commercial sericulture units.

**4. Impact of Biofortified Mulberry on Silkworm Performance**

The nutritional status of mulberry leaves plays a decisive role in shaping the biological efficiency of *Bombyx mori* L. Silkworms are highly responsive to changes in their diet, and even slight improvements in leaf quality can bring about significant enhancements in growth, survival, and silk production. Biofortified mulberry leaves, enriched through agronomic, microbial, or post-harvest methods, have shown promising results in improving several larval and cocoon traits.

The link between leaf nutrition and silkworm physiological response is depicted in **Figure 1**, which summarizes how improved nutrient content supports silk gland development and cocoon formation through enhanced metabolic activity, nutrient absorption, and enzyme regulation.



**Fig.1** *Schematic illustration showing the impact of enhanced nutritional content in biofortified mulberry leaves on silkworm performance and cocoon quality.*

**4.1 Larval Growth and Survival**

Improved nutritional quality of mulberry leaves plays a pivotal role in enhancing larval growth, body weight gain, and developmental uniformity in *Bombyx mori*. High levels of crude protein, amino acids, and digestible carbohydrates in the foliage facilitate rapid cell division and tissue development, especially in the silk glands during the fourth and fifth instars (Mathur et al., 2003; Bongale et al., 1997). Nutritionally superior leaves result in better feed intake and higher assimilation efficiency, leading to shorter larval durations and increased biomass accumulation (Koul and Bhagat, 1994; Ramesh et al., 2011).

Several studies have demonstrated the significant impact of micronutrient supplementation and biological interventions on larval performance. For instance, foliar application of zinc and iron has been shown to enhance protein synthesis and promote overall silkworm vigor (Sannappa & Mallikarjuna, 2009; Sarkar et al., 2017). Similarly, inoculation of mulberry roots with plant growth-promoting rhizobacteria (PGPR) such as *Azospirillum* and *Pseudomonas fluorescens* improves nitrogen uptake and phytohormone production, resulting in nutritionally enriched leaves that support up to 25% greater larval weight and higher survival percentages (Rani et al., 2018; Manjula et al., 2017).

Additionally, the use of organic soil amendments like vermicompost and enriched FYM has shown to enhance leaf nitrogen and phosphorus content, translating into accelerated larval growth and reduced mortality (Kumar et al., 2015; Sharma & Ananthanarayana, 2012). Under controlled experiments, silkworms reared on fermented or amino acid-fortified mulberry leaves exhibited superior metabolic performance and better synchronization of instars compared to those reared on conventional leaves (Lakshmi et al., 2018; Boraiah et al., 2015).

Such improvements not only contribute to the uniformity of silkworm development and batch-wise cocoon harvest but also form the basis for standardized cocoon quality parameters essential for commercial silk production. Therefore, optimized mulberry leaf nutrition stands as a critical factor in achieving enhanced silkworm productivity and economic sustainability of sericulture systems.

**4.2 Cocoon Weight and Shell Ratio**

Cocoon weight and shell ratio are two of the most critical commercial parameters in sericulture as they directly determine silk yield and quality. These traits are highly responsive to the nutritional composition of the mulberry leaves consumed by *Bombyx mori*. Elevated levels of crude protein, total sugars, and essential micronutrients in the foliage have been shown to significantly improve cocoon formation by enhancing silk gland function and protein synthesis (Mathur et al., 2003; Rahmathulla, 2012).

Silkworms enter their peak nutritional demand during the fifth instar, during which silk proteins like fibroin and sericin are synthesized in large quantities. Feeding with leaves fortified with zinc, iron, and magnesium—either through foliar application or PGPR-based biofertilizers—has been reported to improve cocoon weight by 10–20% and shell weight by 15% or more compared to untreated controls (Patil et al., 2014; Ramesh et al., 2011; Sannappa & Mallikarjuna, 2009). These effects are attributed to enhanced enzymatic activities, higher photosynthate availability, and better nitrogen metabolism in the plant, translating into improved nutrient transfer to the silkworm (Sarkar et al., 2017).

Moreover, the cocoon shell ratio—a key indicator of silk recovery potential—is significantly influenced by both macronutrient and micronutrient profiles of the leaves. Nitrogen, particularly in its organic form, supports fibroin synthesis, while adequate moisture improves digestibility and palatability, contributing to better feed conversion (Koul & Bhagat, 1994; Bongale et al., 1997). Varieties such as V1 and S36, when cultivated under integrated nutrient management regimes, consistently produce leaves that result in heavier cocoons and superior shell ratios (Datta, 2000; Lakshmi & Ramesh, 2016).

**4.3 Silk Filament Length and Quality**

The length, strength, and fineness of the silk filament are essential characteristics that determine the commercial value of the cocoon. These parameters are influenced not only by genetic factors but also by the nutritional quality of the larval diet. Silkworms fed with mineral-enriched, fermented, or amino acid-fortified mulberry leaves have been found to produce significantly longer and more uniform filaments with superior reelability and denier consistency (Kavitha et al., 2014; Boraiah et al., 2015).

Leaf supplementation with Spirulina, Chlorella, or protein hydrolysates enhances the amino acid composition of the larval hemolymph, thereby facilitating more efficient fibroin and sericin biosynthesis in the silk glands (Lakshmi et al., 2018; Joshi et al., 2002). This leads to silk threads that are finer, stronger, and less prone to breakage. For instance, Boraiah et al. (2015) reported up to an 18% increase in filament length and notable improvement in uniformity and tenacity when larvae were reared on yeast-fermented leaves.

Micronutrients such as zinc, manganese, and iron also play essential roles in enzymatic activation and oxidative metabolism within the silk gland. Their application through foliar sprays or microbial mediation (PGPR/AMF) enhances the physiological condition of the larvae and stimulates the sericigenic activity of the posterior silk gland (Bindroo & Roy, 2015; Rani et al., 2018). Furthermore, feeding on organically enriched leaves has been shown to yield cocoons with a higher raw silk percentage and reduced waste silk (Ramesh et al., 2011).

Field and lab-based studies support the view that optimizing mulberry leaf nutrient profiles—either through agronomic practices, microbial inoculation, or post-harvest supplementation—can significantly enhance filament characteristics, meeting the needs of both traditional and commercial silk markets.

**4.5 Immunity and Disease Resistance**

Nutritional quality of the diet significantly influences the immune competence of silkworms. Leaves enriched with micronutrients like zinc and magnesium support enzymatic and immunomodulatory functions, including antioxidant defense and stress response mechanisms (Manjula et al., 2017). Silkworms fed on such fortified diets demonstrate higher resistance to microbial infections such as flacherie, grasserie, and muscardine.

Antioxidants and secondary metabolites present in organically enriched or fermented mulberry leaves help reduce oxidative stress during critical growth phases (Lakshmi & Ramesh, 2016). Experimental studies have shown that feeding with PGPR-treated leaves can reduce larval mortality by up to 30%, enhance hemocyte activity, and stimulate enzyme systems such as catalase and peroxidase (Rani et al., 2018; Sarkar et al., 2017). These traits are crucial for maintaining the health and biosecurity of silkworm populations under both controlled and open-rearing systems.

To support the above findings, Table 1 compiles experimental results from various studies evaluating the impact of different mulberry biofortification methods on larval performance and cocoon traits under controlled conditions and Table 2 further illustrates the mode of action of various biofortification approaches and their observed impact on silkworm biology, highlighting the practical relevance of these interventions.

**Table 1. Compiled results from previous studies on the impact of different biofortification methods in mulberry cultivation on silkworm (*Bombyx mori*) growth, cocoon quality, and survival under** **laboratory conditions**.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Treatment Type** | **Larval Weight (g)** | **Cocoon Weight (g)** | **Shell Ratio (%)** | **Filament Length (m)** | **Survival Rate (%)** | **Reference** |
| Control (non-treated leaves) | 3.6 ± 0.1 | 1.35 ± 0.04 | 18.2 ± 0.6 | 850 ± 15 | 85.4 ± 1.2 | Kavitha et al. (2014) |
| ZnSO₄ Foliar Spray (0.5%) | 4.2 ± 0.2 | 1.52 ± 0.05 | 20.6 ± 0.8 | 945 ± 20 | 91.3 ± 1.5 | Kumar et al. (2015) |
| Vermicompost Enriched Leaves | 4.0 ± 0.1 | 1.48 ± 0.03 | 20.1 ± 0.7 | 920 ± 18 | 89.5 ± 1.0 | Manjula et al. (2017) |
| PGPR Treated Leaves | 4.3 ± 0.2 | 1.56 ± 0.05 | 21.0 ± 0.5 | 980 ± 22 | 92.1 ± 1.3 | Rani et al. (2018) |
| Fermented Mulberry Leaf Extract | 4.1 ± 0.1 | 1.50 ± 0.04 | 20.4 ± 0.6 | 930 ± 17 | 90.6 ± 1.1 | Ramesh et al. (2011) |

**Table 2. Summary of nutrient-based and microbial biofortification techniques in mulberry and their effects on *Bombyx mori* growth and silk yield**

|  |  |  |  |
| --- | --- | --- | --- |
| **Nutrient / Fortification** | **Mode of Action** | **Observed Impact on Silkworm** | **Reference** |
| Zinc (Zn) biofortification | Enhances silk gland growth and enzyme activity | Increased cocoon weight and shell ratio | Sarkar et al. (2017) |
| Fermented leaf feed (microbial) | Improves digestibility and nutrient availability | Better larval weight, survival rate | Boraiah et al. (2015) |
| PGPR and Mycorrhiza inoculation | Enhances root nutrient uptake in mulberry | Enriched leaves improve cocoon traits | Koul & Dhaliwal (2019) |
| Foliar micronutrient spray | Boosts leaf protein and sugar content | Improved silk filament length | Bindroo & Roy (2015); Lakshmi & Ramesh (2016) |
| High-nitrogen mulberry varieties | Increases crude protein in leaves | Accelerated larval growth | Dandin et al. (2003) |
| Iron (Fe) supplementation | Improves leaf quality and hemolymph composition | Enhanced metabolic activity in larvae | Bindroo & Roy (2015) |
| Balanced macronutrient fertilization | Increases carbohydrate and moisture in leaves | Boosts silk gland development | Sharma & Ananthanarayana (2012) |

The use of biofortified mulberry leaves has a multifaceted impact on silkworm biology. Enhanced leaf nutrition improves larval performance, cocoon productivity, silk quality, and disease resistance. These benefits demonstrate the potential of nutritional enhancement as a low-cost, high-impact intervention in sustainable sericulture practices.

**5.** **Sustainability and Future Prospects of Mulberry Biofortification**

Incorporating biofortification practices in mulberry cultivation holds significant promise for sustainable sericulture. As global agriculture moves toward eco-friendly and resource-efficient systems, the sericulture sector must align its practices to reduce dependency on chemical inputs while maintaining high productivity. Biofortification especially through biological and agronomic means offers a viable solution to this challenge by enhancing leaf nutritional quality without compromising environmental health.

5**.1 Environmental Sustainability**

Biofortification through microbial inoculants, organic compost, and integrated nutrient management reduces the overuse of synthetic fertilizers and pesticides. These practices contribute to improved soil fertility, enhanced microbial activity, and reduced greenhouse gas emissions (Kumar et al., 2015). The application of plant growth-promoting rhizobacteria (PGPR), such as *Azospirillum*, *Bacillus*, and *Pseudomonas* spp., enhances nitrogen fixation, phosphate solubilization, and nutrient uptake efficiency, which collectively reduce nitrate leaching and chemical residue build-up (Rani et al., 2018; Sannappa & Mallikarjuna, 2009). Additionally, biofortification aids in restoring degraded soils and promotes carbon sequestration through increased root biomass (Narayanan et al., 2006).

**5.2 Economic Viability for Farmers**

Smallholder farmers, who constitute the majority of the sericulture community, can benefit economically from biofortification techniques. Improved cocoon yield, better-quality silk, and reduced disease incidence translate into higher returns on investment. For example, fortified mulberry leaves have been shown to increase silk filament length and cocoon shell weight, directly improving market value (Kavitha et al., 2014; Sarkar et al., 2017). Since many biofortification strategies utilize locally available resources like compost, farmyard manure (FYM), or indigenous microbial strains, adoption is both cost-effective and scalable (Lakshmi & Ramesh, 2016). Moreover, the reduction in chemical inputs leads to additional cost savings and improves long-term farm sustainability.

**5.3 Integration with Climate-Resilient Practices**

Climate variability and soil degradation are emerging challenges in sericulture regions. Biofortification helps develop more resilient cropping systems by improving plant vigor and resistance to abiotic stressors such as drought, salinity, and heat (Manjula et al., 2017; Jaiswal et al., 2022). Fortified mulberry leaves support sustained leaf biomass production under marginal environmental conditions, ensuring consistent silkworm feeding and cocoon development. PGPRs and mycorrhizal fungi also contribute to better water retention in soil and hormone regulation (like increased indole-acetic acid and cytokinin levels), enhancing drought tolerance in mulberry plants (Islam et al., 2018).

**5.4 Future Research Directions**

Despite promising results, biofortification in mulberry is still in its early stages compared to food crops. Future research should focus on identifying nutrient-dense mulberry genotypes using omics-based tools, including transcriptomics and metabolomics, to study the expression of nutrient transporters and storage proteins (Ramesh et al., 2011; Sharma & Ananthanarayana, 2012). Moreover, field-scale studies under different agro-climatic conditions are essential to validate lab and pot-level findings. Research into nanonutrient delivery systems, such as nano-zinc and nano-iron, also holds potential for targeted and efficient leaf enrichment (Jaiswal et al., 2022). Interdisciplinary collaboration between soil scientists, entomologists, and breeders will be critical to advance this field.

**5.5 Policy and Extension Implicatio**ns

For the widespread adoption of biofortification, policy-level support is crucial. Training programs, subsidies for bio-inputs, and demonstration trials can accelerate the uptake of these techniques among sericulture farmers. Inclusion of biofortification modules in sericulture extension manuals and farmer field schools will bridge the knowledge gap and promote sustainable practices (Mathur et al., 2003; Dandin et al., 2003). Government-led certification programs recognizing biofortified leaf production may also incentivize adoption. Strengthening public-private partnerships and research-extension linkages will be instrumental in transformingmulberry biofortification from a niche innovation to a mainstream practice.

**6. Emerging Frontiers: Nano-Biofortification and Molecular Insights in Mulberry Nutrition**

Recent advances in agricultural biotechnology have paved the way for more efficient and sustainable approaches to enhance the nutritional profile of mulberry leaves. Among these, nano-biofortification and molecular-based nutritional understanding represent significant innovations in the field of sericulture. These emerging tools not only improve the nutritional quality of mulberry foliage but also provide insights into the biological responses of silkworms to enriched diets.

**6.1 Nano-Biofortification for Targeted Nutrient Delivery**

Nano-biofortification involves the application of essential micronutrients in nanoscale forms, enhancing their absorption, mobility, and utilization within plant tissues. When applied to mulberry, nano-fertilizers such as nano-zinc (Zn), nano-iron (Fe), and nano-boron (B) have shown enhanced leaf nutrient content, photosynthetic activity, and overall plant vigor (Jaiswal et al., 2022). This improvement in leaf physiology directly translates into better cocoon characteristics in *Bombyx mori*.

For example, foliar spraying of nano-zinc at a concentration of 25 ppm has been shown to improve leaf protein content and larval growth rate, ultimately enhancing cocoon weight and shell percentage (Lakshmi & Ramesh, 2016). The slow-release behavior of nano-fertilizers ensures consistent nutrient availability, thereby reducing nutrient leaching, minimizing environmental degradation, and improving input use efficiency (Sarkar et al., 2017).

**6.2 Molecular Responses of Silkworms to Enriched Mulberry Diets**

The ingestion of nutrient-rich or biofortified mulberry leaves induces physiological and molecular changes in silkworms. Notably, enriched diets lead to upregulation of genes involved in silk gland development, fibroin and sericin synthesis, and metabolic enzyme regulation (Islam et al., 2018). Enhanced nutrient availability, particularly proteins and micronutrients like Zn and Fe, influences hemolymph composition, antioxidant defense mechanisms, and stress tolerance in larvae.

Gene expression studies have indicated that biofortified diets increase the transcription levels of fibroin heavy chain (Fib-H) and sericin 1 (Ser1) genes, which are crucial for silk filament formation. In addition, improved enzyme activities such as superoxide dismutase (SOD) and catalase (CAT) contribute to better oxidative stress management in larvae fed with fortified diets (Manjula et al., 2017). These molecular responses establish a strong link between mulberry leaf enrichment and enhanced silk biosynthesis.

**6.3 Integrated Molecular–Agronomic Approaches for Future Sericulture**

Combining molecular biology with agronomic management offers a holistic strategy for enhancing cocoon yield. The integration of transcriptomic, proteomic, and metabolomic data can aid in the identification of nutrient-efficient mulberry varieties and tailor-made feeding regimens. By aligning plant and insect nutrition, it becomes feasible to develop site-specific management practices that improve both productivity and sustainability.

Future studies should explore the role of nutrient transporters, stress-responsive genes, and silk-specific regulatory proteins in response to fortified diets. Such insights can guide the development of targeted biofortification strategies, enhancing silk output while maintaining ecological balance (Ramesh et al., 2011; Koul & Dhaliwal, 2019).

**7. Climate Resilient Mulberry Cultivation for Sustainable Silk Production**

Climate change presents new challenges for sericulture, particularly in terms of maintaining the quality and quantity of mulberry leaf production. Rising temperatures, erratic rainfall, droughts, and soil degradation adversely affect mulberry physiology, leading to reduced biomass and nutrient levels. Consequently, the health and productivity of silkworms also decline. To address these issues, climate-resilient mulberry cultivation practices are gaining importance in sericultural research and practice.

**7.1 Development of Drought- and Heat-Tolerant Mulberry Genotypes**

Breeding efforts have resulted in the development of mulberry varieties such as RC2, S1635, and VI-1 that exhibit higher tolerance to drought and temperature extremes. These varieties possess traits such as deeper root systems, high leaf moisture retention, better osmolyte accumulation (e.g., proline), and efficient stomatal regulation, which enable them to maintain leaf quality under stress conditions (Rahmathulla, 2012).

Field evaluations have shown that these genotypes maintain relatively stable levels of crude protein and soluble sugars during heat waves, making them suitable for rearing silkworms even in off-seasons. Such climate-adapted varieties are key to sustaining year-round cocoon production.

**7.2 Microbial Interventions for Stress Mitigation**

The application of plant growth-promoting rhizobacteria (PGPR) and arbuscular mycorrhizal fungi (AMF) has been shown to enhance stress tolerance in mulberry plants. These beneficial microbes improve nutrient acquisition, root architecture, and production of stress-alleviating phytohormones such as indole-3-acetic acid (IAA) and abscisic acid (ABA) (Manjula et al., 2017). Additionally, they increase antioxidant enzyme activities in mulberry, mitigating the effects of drought and salinity.

Silkworms fed on leaves from PGPR-treated mulberry plants have shown better weight gain, reduced larval mortality, and improved cocoon traits, even under suboptimal environmental conditions (Rani et al., 2018).

**7.3 Climate-Smart Agronomic Practices**

The implementation of climate-smart cultivation practices such as organic mulching, drip irrigation, and intercropping with legumes plays a critical role in enhancing soil moisture conservation and reducing evapotranspiration losses. Organic mulches help regulate soil temperature, enhance microbial activity, and reduce weed competition, all of which contribute to better mulberry growth and leaf quality (Sharma & Ananthanarayana, 2012).

Drip irrigation systems, when paired with fertigation techniques, ensure uniform nutrient distribution while minimizing water wastage. These water-saving methods are especially important in drought-prone sericulture regions.

**7.4 Long-Term Prospects**

Integrating stress-resilient mulberry varieties, microbial inoculants, and adaptive agronomic techniques holds significant promise for climate-resilient sericulture. These approaches will not only help stabilize mulberry productivity under adverse conditions but also improve the sustainability and profitability of silk farming. Future research should aim to develop decision-support tools and weather-adaptive nutrient schedules tailored for different agro-climatic zones.

**6. Conclusion**

The quality and nutritional composition of mulberry leaves are critical factors that directly influence the physiological performance, growth dynamics, and silk-producing capabilities of the silkworm, *Bombyx mori*. As the exclusive food source for silkworms, the biochemical makeup of mulberry foliage—particularly its protein, carbohydrate, moisture, and micronutrient content—plays a decisive role in determining larval health, metabolic efficiency, and ultimately, cocoon yield and silk quality. Given the intimate relationship between mulberry nutrition and silkworm development, enhancing the nutritive value of these leaves presents a strategic and sustainable opportunity to improve sericultural outcomes.

Recent advancements have highlighted the potential of various interventions—including agronomic practices, microbial applications, and post-harvest treatments—to significantly boost the nutritional quality of mulberry leaves. Agronomic improvements, such as optimized fertilization, soil management, and cultivar selection, have been shown to enhance leaf biomass and nutrient density. Microbial enrichment, particularly through the application of plant growth-promoting rhizobacteria (PGPR) and beneficial fungi, improves nutrient uptake, plant vigor, and resilience to environmental stressors. Post-harvest fortification techniques, such as nutrient dipping or foliar application of micronutrients, offer further avenues for improving leaf quality just before silkworm feeding.

These strategies have demonstrated tangible benefits in sericulture. Improved leaf quality contributes to faster larval development, higher cocoon weights, better shell ratios (the proportion of cocoon shell to total cocoon weight), longer silk filaments, and increased larval survival. These improvements not only enhance raw silk yield and quality but also contribute to reduced production cycles and more consistent cocoon output.

As global demand for natural and high-quality silk continues to rise—driven by the textile, medical, and cosmetic industries—modernizing sericulture through optimized mulberry nutrition is becoming increasingly important. A nutrition-centric approach to mulberry cultivation aligns with global goals for sustainable agriculture, as it reduces reliance on chemical inputs, improves land-use efficiency, and supports climate-resilient practices.

Looking ahead, future research should focus on developing region-specific biofortification protocols that consider local soil conditions, climate variability, and farmer practices. The identification and integration of effective PGPR strains that enhance nutrient uptake and plant growth under diverse field conditions is another key research priority. Furthermore, the development and dissemination of eco-friendly, affordable field technologies—such as compost-based biofertilizers, nano nutrient solutions, or microbial consortia—can make nutritional interventions accessible to smallholder farmers.

A systems-level understanding of the nutritional interactions between mulberry plants and silkworms is essential for unlocking the full potential of this sustainable approach. By addressing both plant and insect nutritional needs, such integrated strategies can drive improvements in silk production, enhance farm incomes, and reinforce the socio-economic foundations of sericulture, particularly in developing countries where it serves as a major livelihood source.

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