

Golden Threads from Healthy Soil: Eco-Friendly Strategies for Mulberry Cultivation

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Abstract

Mulberry (*Morus alba* L.) forms the backbone of sericulture, where leaf quality directly influences silkworm growth, cocoon yield, and silk production. However, conventional chemical-intensive practices, though effective for short-term gains, have resulted in soil degradation, declining microbial diversity, and environmental pollution. To ensure sustainability, eco-friendly nutrient and soil management practices are gaining importance. Organic amendments such as farmyard manure, compost, vermicompost, green manures, and biofertilizers enrich soil structure, enhance microbial activity, and improve leaf nutrient composition. Integrated nutrient management, precision fertilization, mulching, and microbial inoculants further strengthen soil fertility while reducing chemical dependency. These strategies not only boost mulberry leaf protein content and plant vigor but also conserve soil biodiversity and mitigate climate-related stress. By linking healthy soils to sustainable silk production, this review underscores the importance of eco-friendly approaches in mulberry cultivation, to achieve high productivity without compromising ecological balance. By adopting these eco-friendly strategies, sericulture can align with the principles of sustainable agriculture, ensuring "golden threads" of silk are woven from healthy soils while safeguarding environmental integrity

Keywords: *Mulberry cultivation; Soil health; Eco-friendly practices; Sustainable sericulture.*

1. Introduction

Silk, often described as the "queen of textiles," begins its journey in the soil through the cultivation of mulberry (*Morus alba* L.). The vigor and nutritional richness of mulberry leaves serve as the cornerstone of sericulture, shaping silkworm health, cocoon quality, and ultimately the value of silk threads. While chemical fertilizers have historically boosted mulberry yields, their indiscriminate use has also depleted soil organic matter, reduced microbial diversity, and contributed to ecological imbalances.

In contrast, a paradigm shift toward eco-friendly farming is redefining mulberry cultivation. Emphasis is now placed on restoring soil vitality through organic manures, vermicompost, green manures, and biofertilizers, which collectively enhance nutrient availability, soil structure, and resilience against climatic stress. Complementary practices such as integrated nutrient management, precision input use, and microbial inoculants not only support healthier soils but also ensure consistent leaf production with higher protein content. Exploring these strategies is vital

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for achieving sustainable sericulture. By aligning mulberry farming with ecological principles, farmers can secure long-term productivity while reducing environmental footprints.

1.1 Importance of mulberry (*Morus alba*) in sericulture

Mulberry is classified under the family Moraceae, tribe Moreae, genus *Morus*, with *Morus alba* L. (white mulberry) being the most commonly cultivated species. In India, the genus *Morus* is represented by four distinct species, viz., *M. indica*, *M. alba*, *M. serrata* and *M. laevigata*. The natural distribution of the genus has considerably changed because of its extensive cultivation for silkworm rearing (Tikader et al., 2002). Mulberry is an economically important tree being cultivated primarily for its leaves, which serve as the sole food source for the silkworm *Bombyx mori*. Since the quality and quantity of mulberry leaves directly influence larval growth, cocoon yield, and raw silk production, the plant is often regarded as the “life-blood of sericulture.” Rearing of silkworm is an art and science popularly known as sericulture; an agro-based cottage industry that provides sustainable employment to millions in China, India, Korea, and Vietnam (Vijayan et al., 2012).

Beyond its role as a food plant, mulberry plays a pivotal role in determining the economic viability and sustainability of the entire sericulture industry. Healthy mulberry plantations ensure continuous supply of nutritious leaves rich in proteins, vitamins, and moisture, which are essential for optimal silkworm health and cocoon quality. Moreover, being a perennial plant with deep root systems, mulberry contributes to soil conservation, carbon sequestration, and microclimate regulation, thereby supporting eco-friendly cultivation models. Adoption of organic manures, biofertilizers, green manuring, and microbial inoculants in mulberry cultivation not only maintains soil fertility but also enhances leaf quality without the adverse impacts of chemical inputs. Thus, the importance of mulberry extends beyond leaf supply; it underpins ecological sustainability, rural livelihood security, and the global silk economy.

1.2 Nutrient requirements of mulberry for optimal leaf yield and quality

Mulberry is a perennial crop that remains productive throughout the year, particularly in tropical regions, and therefore requires a continuous and balanced supply of nutrients to sustain repeated leaf harvesting. Nitrogen plays a dominant role in promoting vigorous shoot growth, chlorophyll formation, and protein synthesis, which directly determine leaf biomass and nutritive value for silkworm feeding. Phosphorus is essential for strong root development and efficient energy transfer, enabling rapid regeneration of shoots after pruning, while potassium enhances enzyme activity, water regulation, and stress tolerance, improving leaf texture and uniformity. Secondary nutrients such as calcium, magnesium, and sulphur contribute to cell wall strength, chlorophyll synthesis, and amino acid formation, ensuring physiological stability of the plant. Micronutrients, though required in smaller quantities, are crucial for metabolic functions, hormonal balance, and photosynthetic efficiency, and their deficiencies can adversely affect leaf quality. Soil pH and organic matter content strongly influence nutrient availability and uptake, making soil management an integral part of mulberry nutrition. The incorporation of organic manures and biofertilizers improves soil structure, microbial activity, and gradual nutrient release, enhancing nutrient use efficiency. Therefore, balanced and site-specific nutrient management is essential to achieve optimal mulberry leaf yield and quality while sustaining soil health in sericulture-based farming systems.

1.3 Issues with chemical fertilizers: soil degradation, pollution, cost.

Excessive and continuous use of chemical fertilizers in mulberry cultivation has led to several agronomic, environmental, and economic concerns. Long-term reliance on inorganic fertilizers often results in soil degradation through the decline of organic matter, deterioration of soil structure, and reduction in beneficial microbial activity, which ultimately lowers nutrient use efficiency. Chemical runoff and leaching contribute to soil and water pollution, contaminating groundwater and nearby ecosystems with nitrates and phosphates, while also increasing the risk of nutrient imbalance and toxicity in soils. In sericulture systems, such degradation can negatively affect mulberry leaf quality and indirectly impact silkworm health. In addition, the rising cost of chemical fertilizers places a significant financial burden on small and marginal farmers, reducing profit margins and increasing dependency on external inputs.

Alongside fertilizer-related issues, intensive use of chemical pesticides further aggravates soil health problems. The long-term impact of pesticides on soil health depends on both soil and pesticide properties that influence the processes like sorption, biodegradation, chemical transformation, microbial transformation, volatilization, leaching, uptake by the organisms, etc. (Chiaia-Hernandez et al. 2017; Tudi et al. 2021). These processes determine the persistence and mobility of pesticide residues in mulberry soils. Upon application, pesticides are subjected to several environmental processes, including degradation, transport, sorption, and desorption. (Okada et al. 2019; Liu et al. 2021). Repeated exposure can disrupt soil microbial communities, suppress beneficial organisms, and interfere with nutrient cycling, thereby compounding the negative effects already caused by chemical fertilizers. The combined impact of fertilizers and pesticides accelerates soil quality deterioration, increases environmental pollution risks, and undermines the sustainability of mulberry-based sericulture, reinforcing the need for integrated nutrient and pest management strategies that prioritize soil health and long-term productivity.

2. Soil Fertility and Nutrient Requirements

Soil fertility is a fundamental factor determining the growth, yield, and nutritional quality of mulberry (*Morus* spp.), the primary host plant of the silkworm (*Bombyx mori* L.). Optimum soil fertility involves balanced nutrient availability, suitable pH, adequate organic carbon, and active microbial populations. Mulberry performs best in well-drained loamy soils with a pH of 6.2–7.0, where macro- (N, P, K) and micronutrients (Fe, Zn, Mn, B) are available in appropriate proportions. Continuous leaf harvesting often leads to nutrient depletion; therefore, maintaining soil organic matter and microbial activity through organic manures, compost, and biofertilizers is essential. Integrating organic and inorganic nutrient sources ensures sustained productivity, improved leaf quality, and promotes eco-friendly, sustainable sericulture practices.

2.1 .Macronutrients: Nitrogen (N), Phosphorus (P), Potassium (K) needs:

Mulberry being a perennial crop requires a continuous and adequate supply of nutrients to get sustained yield. Due to continuous cultivation of mulberry, the soil nutrient status gets depleted. To overcome this hidden hunger, the application of balanced fertilization of all the three major nutrients, namely nitrogen, phosphorus, and potassium, is essential for the growth and yield of mulberry along with farmyard manure (Ray et al., 1973). Fertilizer, even though costly, is an indispensable input for achieving the total yield potential of mulberry. Without fertilizers, high-yielding varieties perform no better than the local (Manjula, 1993). The yield of mulberry is influenced more by the amount of nitrogenous fertilizer than phosphorus and potassium (Pain, 1965; Kasiviswanathan et al., 1979; Islam et al., 1982 and 1985). Nitrogen is a constituent of protein and therefore a constituent of every living cell (Reisenauer, 1978). Nitrogen has a direct effect on the leaf yield since it controls the vegetative growth, number, size, and weight of leaves. Potassium has been reported as the key nutrient in maintaining mulberry leaf quality, besides its moisture content (Radha et al., 1988). Potassium-deficient crops develop weak stems, and their roots become more easily infected with root-rotting organisms leading to lodging of plants.

In addition to these functions, nitrogen enhances chlorophyll synthesis, improves photosynthetic activity, and ensures higher protein accumulation in mulberry leaves, which directly benefits silkworm growth and cocoon quality. Phosphorus is vital for root development, cell division, and energy metabolism through ATP formation, thereby helping the plant to absorb and utilize other nutrients efficiently. It also strengthens stem structure and accelerates early establishment of mulberry cuttings. Potassium contributes to enzyme activation, osmotic regulation, and carbohydrate translocation within the plant, maintaining leaf turgidity and improving resistance against drought and diseases. A balanced and timely supply of these macronutrients not only supports vigorous plant growth but also enhances the nutritional quality of leaves, ensuring better silkworm health and silk yield. Therefore, adopting an integrated nutrient management approach that combines NPK fertilizers with organic sources like compost or vermicompost is essential to sustain soil fertility, improve leaf productivity, and promote environmentally sustainable sericulture practices. Available phosphorus and potassium are essential macronutrients that promote root development, energy transfer, and stress resistance in mulberry (Mengel & Kirkby, 2001).

2.2 Micronutrients: Iron (Fe), Zinc (Zn), Boron (B), Manganese (Mn) in mulberry growth.

Micronutrients are critical for mulberry growth and directly affect silkworm physiology, cocoon yield, and silk quality by enhancing metabolic pathways and maintaining plant health.

Zinc (Zn) plays a multifaceted role in both plants and silkworms. In mulberry, Zn regulates auxin metabolism, chlorophyll synthesis, and enzyme activation, which collectively improve leaf quality, protein content, and photosynthetic efficiency. In silkworms, the importance of Zn extends further, as it supports enzymatic reactions, hormone regulation, and energy metabolism, all of which contribute to efficient growth and reproduction. The role of mineral nutrition, particularly zinc, needs to be clearly established, as it plays a crucial role in the synthesis of lipids, proteins, and carbohydrates, and contributes to the reduction of larval and pupal durations. (Bhattacharya and Kaliwal, 2005). In silkworm, Zn increases the weight of the larvae and seri gene gland and reduced the mortality rate and the larval duration (Balamani et al., 1995; Hugar and Kaliwal, 1999, 2002; Ashfaq et al., 2010).

Iron (Fe) is equally indispensable as it is a central component of cytochromes, ferredoxin, and other proteins involved in electron transport, respiration, and photosynthesis. In mulberry plants, Fe ensures proper chlorophyll biosynthesis, sugar metabolism, and nitrogen fixation, making it vital for leaf biomass accumulation and nutritional quality. In silkworms, Fe contributes to energy transformation and enzymatic functioning, thereby enhancing the growth and vitality of larvae. Micronutrients, particularly zinc and iron, play a significant role in enhancing metabolic activity in silkworms, thereby improving rearing performance, silk yield, and fecundity (Bose *et al.*, 1995). Furthermore, feeding silkworms with zinc- and iron-enriched mulberry leaves has been shown to significantly increase the fecundity of silk moths (Shankar *et al.*, 1996). Fe is an essential micronutrient for transformation of carbohydrates and regulating consumption of sugars (Kumar et al., 2012)

Manganese (Mn) plays an essential role in both plant and insect physiology. In mulberry, Mn is vital for chlorophyll formation, activation of various dehydrogenases and decarboxylases in the Krebs cycle, and regulation of carbohydrate and protein metabolism. It also supports the assimilation of nitrogen, formation of vitamin C, and improves plant resistance against abiotic stress. In silkworms, adequate Mn in mulberry leaves indirectly improves metabolic efficiency, supporting larval development and silk gland activity. Manganese is necessary for metabolic activities, among the micronutrients, Mn and Zn are important for normal growth of the plants. Manganese functions as an enzyme activator in various growth-related metabolic processes. It is an integral constituent containing superoxide dismutase (Epstein and Bloom, 2005).

Boron (B), Adequate B supply improves mulberry leaf quality and directly impacts silkworm feeding efficiency, as higher sugar translocation contributes to silk protein synthesis and overall cocoon yield. Its deficiency leads to stunted growth, poor leaf expansion, and reduced quality of silkworm feed, thereby underlining its role as a critical micronutrient for sustainable sericulture.

Together, these micronutrients (Fe, Zn, B, and Mn) form a synergistic network that ensures mulberry health, enriches nutrient transfer to silkworms, and enhances silk quality. Their physiological contributions in plants and silkworms highlight their dual importance for sustaining leaf productivity, larval health, and cocoon yield in eco-friendly sericulture systems.

3. Organic Nutrient Sources

Organic nutrient sources play a vital role in maintaining soil fertility and ensuring sustainable mulberry production. Materials such as farmyard manure (FYM), compost, green manures, vermicompost, oil cakes, and biofertilizers are key contributors to soil health and plant nutrition in sericulture systems. These inputs supply essential macro- and micronutrients, improve soil organic carbon, and enhance microbial activity, which together promote better mulberry leaf quality.

3.1 Compost and farmyard manure (FYM):

Organic manures such as farmyard manure (FYM) and compost are vital components in sustainable mulberry cultivation systems. These organic inputs not only enrich the soil with essential nutrients but also enhance its structure, moisture retention, and biological activity, which are critical for long-term soil productivity and healthy mulberry growth. FYM also improves soil water holding capacity. The fact that the use of organic fertilizers improves soil structure, nutrient exchange, and maintains soil health has raised interests in organic farming (Kunj et al., 2018). The use of FYM and compost in combination replenishes soil organic matter, enhances microbial population, and supports nutrient cycling factors that directly contribute to improved mulberry leaf quality and cocoon yield.

Farm yard manure rich in organic matter contents most of the nutrients viz: nitrogen, phosphorus, potassium, calcium, magnesium, iron, manganese, zinc and copper (Venugopal et al., 2010). Similarly, compost prepared from agricultural and sericultural residues provides a slow and steady release of nutrients while improving soil texture and porosity. These organic amendments promote better root development and nutrient uptake in mulberry plants, ensuring consistent leaf yield. In addition, FYM has a great impact on leaf yield contributing characters and it can significantly reduce the infestation of foliar diseases like leaf spot, powdery mildew and tukra of mulberry plant (Ahmed et al., 2022).

3.2 Vermicompost:

Most of the silkworm host plants are perennial in nature, because of which, once they are planted, they are maintained for several years through continuous agronomical practices at timely intervals. To sustain these plantations, farmers often rely on chemical-based inputs for quick results. However, while these inputs may show short-term benefits, silkworm rearers eventually experience negative effects on leaf yield and cocoon production. Continuous use of chemical fertilizers leads to depletion of essential soil nutrients and deterioration of soil health and environmental quality.

Organic nutrient management, therefore, offers a holistic and sustainable alternative. It integrates various organic inputs to maintain soil fertility, fulfill plant nutrient requirements, and minimize environmental degradation. In sericulture, this approach holds special significance since silkworms are entirely dependent on mulberry leaves for nutrition. Organic inputs ensure slow and steady nutrient release, maintaining leaf quality without the risk of nutrient toxicity or imbalance commonly observed in chemical-intensive systems. The growth and development of mulberry plants are highly dependent on organic nutrients, which enhance resistance to environmental stress, pests, and diseases.

The major sources of organic nutrients for sericulture include farmyard manure (FYM), compost, green manure, biofertilizers, and vermicompost. These materials enrich the soil with essential macro- and micronutrients, improve soil structure, and enhance microbial activity, leading to improved mulberry leaf yield and quality. The integrated application of FYM and vermicompost resulted in higher economic returns in mulberry-based sericulture compared to the application of FYM alone (Chowdhury et al., 2013). This combined use not only enhances nutrient availability but also improves soil aeration and water retention capacity.

Furthermore, the sericulture industry itself generates substantial organic residues that can be effectively recycled. It is estimated that approximately 15 MT of sericultural waste is generated annually from one hectare of mulberry cultivation, primarily in the form of silkworm rearing waste and other farm residues, which is equivalent to 280–300 kg of nitrogen, 90–100 kg of phosphorus, and 150–200 kg of potash (Das et al., 1997). These residues can be efficiently converted into valuable compost or vermicompost, reducing dependence on synthetic fertilizers while promoting circular nutrient flow within the farm system.

Overall, the integration of organic nutrient sources not only sustains soil productivity and ecological balance but also contributes to improved mulberry leaf yield and quality, ultimately supporting superior cocoon and silk production in a sustainable manner.

3.3 Green manuring:

Green manuring is a vital strategy in sustainable mulberry cultivation, as it enhances soil fertility, improves soil texture, and promotes long-term productivity without relying heavily on chemical fertilizers. Green manuring in mulberry with Dhaincha (*Sesbania aculeata*) and sun hemp (*Crotalaria juncea*) @ 15 kg seeds/acre is recommended for alkaline and neutral soil conditions respectively (Sakthivel et al., 2014). These leguminous crops enrich the soil by fixing atmospheric nitrogen and improving soil aeration, thereby creating favorable conditions for mulberry root growth and nutrient absorption.

3.4 Biofertilizers:

Bio-fertilizers are biologically active products or microbial inoculates containing living cells or latent cells of efficient strains of microorganisms like bacteria, algae and fungi alone or in combination. They enhance soil fertility by biologically fixing atmospheric nitrogen, solubilizing essential nutrients, and stimulating plant growth through the production of phytohormones. (Somers et al., 2004). They enhance microbial activity, thereby increasing the availability of nutrients in forms that are readily absorbed by plants (Raja, 2013). 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). The application of biofertilizers has been reported to significantly enhance plant height, leaf number, shoot proliferation, and total leaf yield per plant in mulberry, particularly when used in combination with micronutrients (Nazar et al., 2019). In addition, biofertilizer application increases the nitrogen and protein content of mulberry leaves, thereby improving their nutritional quality for silkworms and ultimately enhancing silk quality (Pavankumar et al., 2024). Biofertilizers are living microbial inoculants that promote plant growth by fixing atmospheric nitrogen, solubilizing essential nutrients such as phosphorus and potassium, and producing growth-promoting phytohormones (Fatimah et al., 2021). Nitrogen is one of the most critical and often limiting nutrients required for plant growth. *Rhizobium* establishes a mutualistic relationship with the roots of leguminous plants, where it induces the formation of nodules that serve as biological “factories” for converting atmospheric nitrogen (N_2) into ammonia (NH_3) a form usable by plants. This biological nitrogen fixation process substantially improves soil fertility and can replace up to 300 kg N ha⁻¹ year in legume-based cropping systems (Pindi, 2012). *Azotobacter*, a free-living nitrogen-fixing bacterium, plays a significant role in the nitrogen cycle through its diverse metabolic functions (Sahoo et al., 2014). Unlike *Rhizobium*, *Azospirillum* does not form nodules but instead colonizes the rhizosphere and sometimes the root interior of host plants, where it establishes a loose symbiotic relationship (Nosheen et al., 2021). Mycorrhizae enhance plant growth by stimulating the production of growth-promoting hormones and strengthening plant defense mechanisms against soil-borne pathogens (Dwivedi et al., 2015). Vesicular–arbuscular mycorrhizae (VAM) further facilitate efficient nutrient exchange between the soil and host plants, thereby improving nutrient uptake efficiency (Douds et al., 2000).

4. Sustainable Fertilization Strategies

Sustainable fertilization strategies focus on maintaining soil fertility, optimizing nutrient use efficiency, and minimizing environmental degradation through balanced and eco-friendly nutrient management practices. These approaches integrate the use of organic manures, biofertilizers, green manures, and minimal chemical fertilizers to achieve long-term soil productivity without compromising environmental health. In the context of mulberry cultivation, sustainable fertilization ensures the steady supply of essential nutrients required for healthy leaf production, which directly influences silkworm growth and cocoon quality. By emphasizing nutrient recycling, soil biodiversity enhancement, and reduced dependency on synthetic inputs, these strategies contribute to resilient agro-ecosystems and sustainable sericulture development.

4.1 Integrated nutrient management (INM) combining organic, biofertilizers, and minimal chemical fertilizers.

Integrated Nutrient Management (INM) combining organic, biofertilizers, and minimal chemical fertilizers is an ecologically balanced and economically viable approach to enhance soil fertility, crop productivity, and sustainability in mulberry cultivation. This system emphasizes the synergistic use of diverse nutrient sources to optimize nutrient

availability while maintaining soil health over time. 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. This demonstrates that integrating multiple nutrient sources provides a more balanced and continuous nutrient supply than relying solely on synthetic fertilizers. The inclusion of biological and organic amendments ensures better nutrient synchronization with crop demand and minimizes environmental losses due to leaching or volatilization. A broader integrated organic farming approach along with chemical fertilizers, organic manures, green manures, and bio-fertilizers has also been shown to maintain steady crop production over extended periods (Nambiar and Abrol, 1992; Anilkumar and John, 1999). Such systems contribute to the gradual improvement of soil physical and biological properties, preventing degradation and ensuring long-term productivity. In mulberry cultivation, this is particularly important since the crop is harvested multiple times per year and places a heavy nutrient demand on the soil. The balanced input of organic and inorganic nutrients ensures the continuous replenishment of essential elements without exhausting soil reserves.

Organic manures play a vital role within the INM framework as natural sources of nutrients that improve soil health, enhance microbial activity, and provide slow-releasing nutrients to the crop (Shaji et al., 2021). Their decomposition releases essential macronutrients and micronutrients gradually, aligning with plant uptake rates. Moreover, organic matter serves as a reservoir for the gradual release of nutrients to crops, while also enhancing soil structure, water-holding capacity, and aeration (Ali et al., 2019). This improvement in soil structure reduces erosion, promotes root penetration, and enhances moisture retention—key factors for sustaining mulberry growth under varying climatic conditions. Additionally, organic amendments stimulate beneficial microbial activity, which further accelerates nutrient mineralization and promotes soil enzyme activity essential for nutrient cycling. Integrated Nutrient Management (INM) strategies are instrumental in preserving long-term soil fertility through the enhancement of key soil attributes, including its physical structure, chemical composition, and biological activity (Nakade et al., 2021). These strategies not only maintain the nutrient balance but also help build soil resilience against degradation. By integrating organic residues such as farmyard manure, compost, and green manures with biofertilizers, INM enhances nutrient-use efficiency and soil productivity over time. Integrated Nutrient Management (INM) optimizes nutrient recycling within the soil ecosystem through the incorporation of organic residues and the use of biofertilizers. These practices facilitate the mobilization and sustained availability of essential nutrients such as nitrogen (N), phosphorus (P), and potassium (K) to crops (Imran, 2024). This nutrient recycling process ensures that the soil remains biologically active and self-sustaining, reducing dependence on external fertilizer inputs. Another significant benefit of INM is its positive impact on soil biodiversity. Integrated Nutrient Management (INM) practices contribute significantly to maintaining soil biodiversity by enhancing microbial populations and creating a conducive environment for beneficial microorganisms (Verma et al., 2023). Biofertilizers such as *Azotobacter*, *Azospirillum*, and phosphate-solubilizing bacteria work in conjunction with organic matter to stimulate rhizosphere microbial activity, leading to improved nutrient solubilization and uptake. This microbial enrichment enhances soil fertility, disease suppression, and nutrient efficiency, resulting in healthier and more productive crop. The integration of organic, biofertilizer, and chemical fertilizer inputs within an INM framework promotes a sustainable nutrient management system that enhances both productivity and environmental quality. It ensures a continuous nutrient supply, improves soil health, and maintains the ecological balance necessary for long-term agricultural sustainability. For mulberry cultivation in particular, INM not only boosts leaf yield and quality but also enhances the nutritional composition of leaves, which directly contributes to superior silkworm growth and improved silk yield. Thus, Integrated Nutrient Management represents a cornerstone for sustainable sericulture development merging productivity, profitability, and environmental stewardship into one holistic approach.

4.2 Precision nutrient management using soil testing and plant monitoring.

Precision nutrient management using soil testing and plant monitoring represents a modern and sustainable approach to optimize nutrient use efficiency in crops like mulberry. This strategy involves a scientific assessment of soil fertility, crop nutrient uptake patterns, and environmental conditions to provide the right quantity of nutrients at the right time and in the right form. Regular soil testing helps determine nutrient deficiencies or toxicities, while plant tissue analysis provides insight into the actual nutrient absorption status of the crop. Together, these tools enable farmers to make informed decisions that enhance productivity without compromising soil health.

This approach ensures that fertilizers, whether organic or inorganic, are applied precisely based on the site-specific needs of the soil and crop, thereby improving nutrient-use efficiency and minimizing nutrient losses through leaching or volatilization. Moreover, the integration of technology such as remote sensing, digital soil maps, and decision-support tools further refines precision management, allowing real-time monitoring of crop performance. Specific Nutrient Management is a strategy aimed at enhancing crop productivity and sustaining soil health by providing a nutrient supply tailored to the specific needs of both the crop and the soil (Shyam et al., 2021). However, despite its potential, the full-scale adoption of precision nutrient management is often limited by logistical constraints, particularly in rural and resource-poor areas where access to high-quality organic manures, biofertilizers, and micronutrient formulations remains inadequate. The availability of high-quality organic manures, biofertilizers, and micronutrient formulations remains a major challenge, particularly in remote or resource-limited areas (Bayu, 2020). In the context of mulberry cultivation, precision nutrient management can be highly beneficial when integrated with strategic farming practices. These include soil-specific fertilizer scheduling, split application of nitrogen, and balanced use of organic manures, compost, and biofertilizers to maintain consistent leaf quality for silkworm rearing. The use of leaf nutrient indexing helps monitor the mulberry plant's nutritional status, ensuring timely correction of deficiencies. Additionally, drip fertigation systems enable uniform nutrient delivery and efficient water use, while crop rotation with legumes improves biological nitrogen fixation and reduces the dependency on chemical fertilizers. Incorporating green manuring crops like sunn hemp or cowpea before mulberry planting can also enhance soil organic matter and improve nutrient cycling efficiency.

5. Challenges and Research Gaps

Despite the importance of healthy soil in sustainable mulberry cultivation, several challenges limit the adoption of eco-friendly practices. Limited availability and lack of standardization of biofertilizers lead to inconsistent field performance. The interactions between soil microorganisms and mulberry nutrient dynamics are not fully understood across diverse agro-climatic conditions. Most studies emphasize short-term yield gains, leaving gaps in long-term soil health and ecosystem resilience. Region-specific integrated soil management strategies combining biological and organic inputs are still inadequate. Bridging these research gaps is essential to strengthen sustainable and environmentally responsible mulberry production.

5.1 Slow nutrient release from organic sources.

One of the major challenges in adopting organic soil amendments in mulberry cultivation is the slow and gradual release of nutrients from materials such as farmyard manure, compost, and green manures. These organic inputs undergo microbial decomposition before nutrients become available to plants, which often leads to delayed nutrient supply, especially during critical growth stages when mulberry requires immediate and readily available nitrogen for leaf production. This mismatch between nutrient demand and release can result in reduced leaf yield, inconsistent leaf quality, and lower protein content, ultimately affecting silkworm growth and cocoon performance. The nutrient release rate is further influenced by environmental factors such as temperature, soil moisture, and microbial activity, making it unpredictable across seasons. Therefore, despite their long-term benefits to soil health, the slow mineralization of organic inputs remains a significant limitation, highlighting the need for optimized application schedules, integrated use with faster-acting fertilizers, or the development of enhanced organic formulations to meet the continuous nutrient requirements of mulberry plantations.

5.2 Need for site-specific nutrient management recommendations

Nutrient absorption and accumulation vary widely among mulberry cultivars due to their genetic diversity, environmental factors, and soil nutrient availability (Mithilasri et al., 2023). These inherent differences mean that a single, uniform fertilization schedule cannot meet the nutritional requirements of all cultivars grown under varied agro-ecological zones. Environmental and geographical variations have significant impacts on the nutritional profile of mulberry cultivars (Arfan et al., 2020). Soil properties such as pH, organic matter, moisture regime, and micronutrient distribution differ substantially across regions, influencing the uptake efficiency of essential nutrients like N, P, K, Zn, Fe, and Mn. Some cultivars respond well to high nitrogen inputs, while others show better performance under balanced or micronutrient-rich fertilization regimes. These variable responses highlight the need

for site-specific nutrient management strategies that account for cultivar type, soil characteristics, climatic conditions, and cropping intensity. Tailoring nutrient schedules through soil testing, leaf nutrient diagnosis, and nutrient budgeting can help prevent deficiency or toxicity, improve fertilizer-use efficiency, and reduce production costs for farmers. Therefore, location-specific recommendations are essential to maximize mulberry leaf yield, enhance leaf nutritional quality for silkworm feeding, and promote sustainable nutrient management in sericulture systems.

5.3 Limited availability and standardization of biofertilizers.

Therefore, emphasis has been recently shifted to replace chemical fertilizers with biological materials (Sudhakar et al., 2000).” Beneficial effect of application of Azotobacter in mulberry leaf production was established and demonstrated by Das et al. (1990, 1994 and 1996), Gangwar and Thengavelu (1992).” “Advantages of foliar application of bacterial biofertilizer on mulberry leaf production were also reported by Sudhakar et al. (2000).” Despite these proven benefits, the large-scale adoption of biofertilizers in mulberry cultivation is still constrained due to their limited availability, inconsistent quality, and lack of proper standardization. Variations in microbial strains, carrier materials, shelf life, and storage conditions often result in fluctuating field performance. In many regions, biofertilizers are produced by small-scale units without strict quality control measures, leading to reduced viability of beneficial microorganisms at the time of application. Moreover, the absence of uniform guidelines for formulation, dosage, and application methods further limits their effective utilization by farmers. These constraints highlight the need for standardized production protocols, quality assurance mechanisms, and improved distribution systems to ensure reliable and consistent performance of biofertilizers in mulberry leaf production.

6. Future Perspectives

Future sericulture will increasingly rely on nano-organic fertilizers and microbial consortia to enhance nutrient use efficiency, soil health, and mulberry leaf quality while reducing chemical inputs. The integration of organic mulberry cultivation with precision agriculture technologies such as AI, IoT, GIS, and remote sensing will enable site-specific, data-driven crop and silkworm management. Digital tools will improve monitoring of environmental conditions, pest and disease dynamics, and nutrient requirements, enhancing productivity and resilience. Adoption of renewable energy and eco-friendly processing technologies will reduce carbon footprint and production costs. Together, these approaches will promote sustainable sericulture aligned with global environmental and livelihood goals.

6.1 Development of nano-organic fertilizers for controlled release.

The development of nano-organic fertilizers has emerged as a promising strategy for achieving controlled and efficient nutrient release in mulberry cultivation. By combining organic nutrient sources with nanotechnology-based delivery systems, these fertilizers enhance nutrient retention and availability in the soil–plant system. Studies have demonstrated that nano-fertilizers can significantly improve nutrient use efficiency (NUE) in various crops, including mulberry. Haydar et al. (2024) reported that nano-fertilizers enhanced nutrient uptake and utilization efficiency in mulberry, resulting in increased leaf yield and improved quality. Furthermore, nano-fertilizers can be designed to deliver nutrients in a controlled and stage-specific manner, aligning nutrient release with crop demand and thereby improving NUE and sustainability in mulberry cultivation. Such controlled-release nano-organic formulations reduce nutrient losses, support balanced nutrition throughout crop growth, and contribute to environmentally sustainable mulberry production.

6.2 Use of microbial consortia to enhance nutrient uptake.

The use of microbial consortia has gained importance as an eco-friendly strategy to enhance nutrient uptake in mulberry cultivation. Microbial consortia comprising nitrogen-fixing bacteria, phosphate-solubilizing microorganisms, potassium mobilizers, and plant growth–promoting rhizobacteria act synergistically to improve nutrient availability and absorption by mulberry plants. These beneficial microorganisms enhance root growth, stimulate enzymatic activity, and improve soil nutrient dynamics, leading to better nutrient use efficiency. In addition, microbial consortia contribute to improved soil structure and microbial diversity, which support sustained nutrient cycling. Their integrated action not only enhances mulberry leaf yield and quality but also reduces dependency on

chemical fertilizers. Overall, microbial consortia-based approaches promote sustainable nutrient management and long-term soil health in mulberry cultivation.

6.3 Integration of organic mulberry cultivation with precision agriculture technologies.

By using digital technology, production may be further enhanced and the gap can be overcome. Artificial Intelligence (AI), the Internet of Things (IoT), image processing systems, and other computer-based technologies will undoubtedly improve the quality of the produce when used in the right combination. These technologies enable precise monitoring and management of organic inputs, reducing wastage and improving sustainability. Data is the fundamental component of databases, maps, and models created in sericulture using Geographic Information Systems (GIS), another subset of computer information systems (Chaturvedi, 2018). GIS-based decision support systems help in site-specific planning of organic mulberry cultivation practices. The seasonal changes in environmental elements such as temperature and humidity influence the genotypic composition, which is reflected in commercial characteristics such as shell weight, cocoon weight, and shell ratio percentage (Rahmathulla, 2012). Understanding these variations allows precision tools to adjust cultivation and rearing conditions under organic systems. AI-powered remote sensing and machine learning models help analyze soil health, detect nutrient deficiencies, and predict irrigation needs, ensuring optimal mulberry growth (Sharma and Patel, 2021). This supports efficient organic nutrient and water management while maintaining soil health. Drone-based AI surveillance enables real-time monitoring of plantation health, identifying pest infestations and diseases early for timely intervention (Kumar et al., 2022). Early detection reduces dependence on chemical control measures and supports eco-friendly plant protection. Computer vision techniques assess leaf quality, allowing automated sorting and classification to enhance silkworm nutrition (Gupta and Rao, 2020). Improved leaf quality assessment directly contributes to better cocoon yield in organic sericulture. AI-based predictive models analyze environmental conditions, such as temperature and humidity, to determine the optimal feeding schedule for silkworms, ensuring better nutrient absorption and growth (Sharma and Gupta, 2021). Such precision feeding strategies enhance productivity while maintaining organic production standards.

7. Conclusion:

Sustainable sericulture relies on healthy mulberry cultivation supported by improved soil fertility and efficient nutrient management. Excessive dependence on chemical fertilizers degrades soil health and threatens long-term productivity, whereas organic inputs, nano-organic fertilizers, and microbial consortia enhance nutrient use efficiency, soil microbial activity, and mulberry leaf quality. The integration of precision agriculture and digital technologies enables data-driven, climate-resilient management of mulberry fields and silkworm rearing. Eco-friendly practices reduce environmental impacts while improving productivity and farmer profitability. Overall, the adoption of sustainable and technology-enabled approaches positions sericulture as an environmentally responsible and economically viable agro-enterprise aligned with global sustainability goals.

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