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Integrated nutrient management in tropical mulberry gardens: Recycling sericulture waste for soil health sustainability

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Abstract

Integrated nutrient management (INM) provides a sustainable framework for enhancing productivity, soil fertility, and environmental resilience in tropical mulberry-based sericulture systems. With high frequency of leaf harvesting, warm climates and abundant rain in these areas increases the pace of nutrient cycling, which tends to lose nitrogen, phosphorus and potassium and exhausting the soil organic carbon. INM addresses these challenges by combining chemical fertilizers with organic amendments such as composted mulberry pruning's and silkworm litter, vermicompost, and digestates, alongside biofertilizers including Nitrogen-fixing bacteria, Phosphate-solubilizing microbes, and Arbuscular mycorrhizal fungi. The integrated method enhances physical, chemical, and biological properties of the soil, as well as the aggregate stability, cation exchange capacity, microbial biomass, and enzyme activities, which contribute to increased mulberry leaf yield around 25 per cent, protein and carbohydrate content, and uniform leaf quality throughout different harvests, which promote better silkworm growth and cocoon performance. Also, INM lowers nutrient loss, balances soil nitrogen, augments organic carbon, and diminishes greenhouse gas effects, which lead to climate resiliency. By providing economic advantages, INM reduces reliance on synthetic fertilizers and improves the benefit-cost ratios, however, it demands labour, technical expertise and infrastructure. By synchronizing nutrient supply with crop demand and recycling sericulture residues, INM integrates agronomic efficiency with environmental sustainability, offering a practical, climate-smart model for resilient and productive tropical sericulture systems.

Keywords: Integrated Nutrient Management (INM), mulberry cultivation, sericulture waste recycling, soil health, vermicomposting, sustainable sericulture

1. Introduction

Tropical mulberry (*Morus* spp.) cultivation forms the backbone of sericulture in regions such as southern India, supporting multi-harvest systems with 5-6 leaf harvests annually under irrigated conditions. These are systems with high temperatures (25-35 °C), and high rainfall (more than 1000 mm/year) that cause the breakdown of organic matter and mineralization of nutrients at an accelerated rate, frequently leading to temporary imbalances between nutrient release and crop demand (Palm *et al.*, 2001; Lal, 2015) [28, 22]. Nitrogen (N) is the most important nutrient with respect to leaf biomass production and accumulation of crude protein that has a direct impact on the larval growth and quality of cocoons (Bongale *et al.*, 1997) [9]. Recommended rate of nitrogen application in tropical irrigated garden is 300-350 kg N ha⁻¹ yr⁻¹, while leaf removal alone can account for 250-300 kg N ha⁻¹ annually (Ashaq *et al.*, 2025) [4].

Alfisols and Ultisols, which are the most common tropical soils, have a limited nitrate retention potential, resulting in the loss of 30-50 per cent of the applied nitrogen through leaching or volatilization (Zhang *et al.*, 2015) [50]. The frequent utilization of urea without organic buffering may lead to the increase of soil acidity, which lowers the saturation of the bases and nitrogen supply in the long term (Tian and Niu, 2015) [43]. These systems are also limited by phosphorus (P) and potassium (K). Fixation of phosphorus by iron oxide and aluminium oxides is strong enough to recover less than 20 per cent of recommended doses of 100-150 kg P₂O₅ ha⁻¹ yr⁻¹ to limit growth of the leaf and its photosynthetic capacity. Exchangeable K can decrease by up to

40 per cent in 3-4 years in light-textured soils that are prone to leaching and reduce stomatal control, carbohydrate allocation, and translocation of protein to leaves (Zorb *et al.*, 2014) ^[51]. The main regulator of nutrient retention, microbial activity and aggregate stability is Soil Organic Carbon (SOC), which becomes significantly lower than 0.75 per cent in intensive management of tropical mulberry gardens, and would equate to a 2-3 MT C ha⁻¹ loss over ten years (Six *et al.*, 2002; Lal, 2015) ^[37, 22]. Integrated nutrient management (INM) can replace it by applying chemical fertilizers with organic amendments, i.e., composted mulberry pruning's and silkworm litter, vermicompost, and digestate, which are complemented by biofertilizers, such as nitrogen-fixing bacteria, phosphate-solubilizing microbes, and Arbuscular mycorrhizal fungi (Mahajan *et al.*, 2008; Choudhury *et al.*, 2020) ^[25, 11]. INM not only increases nutrient availability and uptake efficiency, but also improves soil structure, microbial biomass, enzyme activity, and nutrient retention, reducing environmental losses and increasing multi-harvest productivity (Roy *et al.*, 2006; Sannappa *et al.*, 2012; Zhang *et al.*, 2016) ^[31, 32, 48]. The synchronization of nutrient release and crop demand enables INM to overcome the constraints of rapid nutrient cycling,

nutrient fixation, and leaching and enable high-quality leaf production to sustain reliable silkworm productivity across tropical Mulberry-agroecosystems.

2. Nutrient Dynamics and Soil Fertility Constraints in Tropical Mulberry Systems

2.1 Accelerated Nutrient Cycling in Tropical Mulberry Gardens

The high temperature range of 25-35 °C and yearly rainfall of over 1000 mm of tropical mulberry ecosystems promote rapid decomposition of organic matter and mineralization of nutrients (Lal, 2015) ^[22]. It has been shown that soil organic nitrogen can mineralize with rates of 2-3 per cent per month, with a resultant peak in nutrient release that does not always coincide with uptake of mulberry due to the 5-6 leaf harvests annually of high yielding tropical systems (Palm *et al.*, 2001; Dandin, 2014) ^[28, 12]. This imbalance leads to higher chances of nitrogen leaching and volatility, reducing the effectiveness of the fertilizers and escalating production expenses and environmental hazards. A summary of nutrient requirements and nutrient removal in tropical mulberry cultivation is presented in Table 1.

Table 1: Nutrient Requirements and Annual Removal in Tropical Mulberry Systems

Nutrient	Recommended Application (kg ha ⁻¹ yr ⁻¹)	Nutrient Removal through Leaf Harvest (kg ha ⁻¹ yr ⁻¹)	Key Functions in Mulberry	References
Nitrogen (N)	300-350	250-300	Leaf biomass production, protein synthesis for silkworm nutrition	Bongale <i>et al.</i> , 1997 ^[9] ; Ashaq <i>et al.</i> , 2025 ^[4]
Phosphorus (P ₂ O ₅)	100-150	40-60	Root development, photosynthesis, energy transfer	Hinsinger, 2001 ^[16] ; Roy <i>et al.</i> , 2006 ^[31]
Potassium (K ₂ O)	120-180	120-180	Stomatal regulation, carbohydrate transport, leaf quality	Zorb <i>et al.</i> , 2014 ^[51]

2.2 Nitrogen Dynamics and Constraints.

The most vital nutrient to the growth of mulberry leaves is nitrogen which has a direct impact on the larval growth and quality of silk (Bongale, 1997) ^[9]. Recommended rate of nitrogen application in tropical irrigated garden is 300-350 kg N ha⁻¹ yr⁻¹, while leaf removal alone can account for 250-300 kg N ha⁻¹ annually (Ashaq *et al.*, 2025) ^[4]. Regardless of these high inputs, the tropical soils, in particular, Alfisols and Ultisols, have a low cation exchange capacity (CEC), which leads to the estimation of 30-50 per cent of the applied N as losses through leaching or volatilization (Zhang *et al.*, 2015) ^[50]. The frequent utilization of urea without organic buffering may lead to the increase of soil acidity, which lowers the saturation of the bases and nitrogen supply in the long term (Tian and Niu, 2015) ^[43].

2.3 Phosphorus Fixation in Weathered Soils

Phosphorus is a common constraint in tropical mulberry systems because phosphorus is strongly fixed by iron oxides and aluminium oxides in highly weathered soils. The recovery efficiency of applied P fertilizers is usually lower than 20 per cent even with suggested doses of 100-150 kg P₂O₅ ha⁻¹ yr⁻¹ (Hinsinger, 2001) ^[16]. The deficiency of phosphorus limits the growth of leaves and photosynthetic rate, which could lower the yield of the leaves by up to 15-20 per cent in non-integrated fertilizer regimes.

2.4 Potassium Depletion and Leaf Quality Implications

Mulberry needs a large amount of potassium to regulate stomata, osmotic adjustment, and carbohydrate partitioning, and the annual removal rates of 120-180 kg K₂O ha⁻¹ are recorded when it is harvested intensively to harvest leaves (Zorb *et al.*, 2014)

^[51]. Light-textured soils in tropical areas are easily susceptible to K leaching especially during monsoonal precipitation, causing a reduction in exchangeable K of up to 40 per cent after 3-4 years without organic replenishment. Unbalanced N:K ratios are related to a decrease in the translocation of protein to leaves, decreased quantity of soluble sugars, and ineffective growth of silkworms.

2.5 Soil Organic Carbon

SOC acts as a primary regulator of nutrient retention, aggregate stability, and microbial activity. As a result of heavy monocropping and unceasing removal of leaves, SOC levels frequently decrease to less than 0.75 per cent in tropical mulberry gardens (Lal, 2015) ^[22]. It has been shown that in non-amended systems SOC may decline by 0.1-0.3 per cent per decade which amounts to 2-3 MT C ha⁻¹ loss in 10 years (Six *et al.*, 2002) ^[37]. Reduced SOC reduces aggregate stability, with possible losses of 15-25 per cent in water-stable aggregates, making it more vulnerable to erosion as a result of high-intensity rainfall events and augmenting nutrient losses.

2.6 Integrated Perspective on Fertility Constraints

Limitation of nutrient in tropical mulberry soils is not only related to the lack of adequate fertilizer use but it is aggravated by the high rate of the nutrient cycling, fixation of phosphorus, erosion of potassium, and degradation of SOC. These limitations significantly decrease the nutrient use efficacy, less than 50 per cent of the nitrogen in many instances, and reveal the importance of combined nutrient management methods that tackle the chemical and structural limitations in soils and boost biological mediation of nutrients (Palm *et al.*, 2001; Lal, 2015;

Zhang *et al.*, 2015)^[28, 22, 50].

3. Integrated Nutrient Management (INM) Strategies in Mulberry

3.1 Principles of INM in Tropical Mulberry Systems

INM is a technique of maximizing nutrient supply by integrating mineral nutrients with organic nutrients such as amendments and biofertilizers as a means of maintaining the soil fertility and crop yields (Mahajan *et al.*, 2008)^[25]. In crops which grow perennially and offer a multi-harvest, including mulberry, it is essential to synchronize release of nutrients with crop demand. INM methods do not only complement with macro- and micro-nutrients but even improve the soil structure, microbial biomass, nutrient retention, reducing the dangers of exclusive fertilization with chemicals (Roy *et al.*, 2006)^[31].

3.2 Nitrogen Management

INM involves partial replacement of mineral nitrogen with organic sources. Adding composted sericulture wastes or farmyard manure in 5-7 MT ha⁻¹ yr⁻¹ can provide 25-50 per cent nitrogen requirements, striving to enhance the nitrogen use effectiveness by 10-20 per cent relative to full chemical fertilization (Choudhury *et al.*, 2020)^[11]. Biological fixation and mineralization of available N is also improved by biofertilizers which include nitrogen-fixing bacteria, among them *Azotobacter* and *Azospirillum*, which increase yield (8-15%) when used with lower levels of mineral N (Adesemoye and Kloepper, 2009; Adesemoye *et al.*, 2009)^[1, 2]. Split applications in line with the harvest periods also minimize losses through leaching and volatilization, which occur at very high levels in tropical irrigated systems.

3.3 Phosphorus Optimization

Tropical soils have low phosphorus recovery because they have a high fixation. INM uses organic acids which are emitted when the residue is broken down and dissolves Iron and Aluminium attached Phosphorus, leading to uptake by the plant (Sharma *et al.*, 2013)^[34]. Phosphate-solubilizing bacteria, Arbuscular mycorrhizal fungi, can substitute 20-30 per cent of the chemical P requirements without reducing the yield of leaves (Binswanger-Mkhize, 2016)^[7]. Field experiments on tropical mulberry systems indicate that 60-80 kg P₂O₅ ha⁻¹ applied together with organic amendments can be used to ensure leaf P levels remain at 0.25-0.35 per cent dry weight to Favor optimum protein synthesis to support silkworm growth.

3.4 Potassium Management

The Potassium content of mulberry pruning's and silkworm

litter is high (1.2-2.5%), and when they are added to the soil, 40-50 per cent of the K taken annually is restored (Sannappa *et al.*, 2012)^[32]. Organic amendments enhance the retention of exchangeable potassium, which enhances cation exchange sites (especially in sandy or light-textured soils that are subjected to K leaching) (Zorb *et al.*, 2014)^[51]. The exchangeable K of above 120 kg⁻¹ is maintained to maintain the stomatal regulation and carbohydrate translocation to produce high-quality leaves.

3.5 Role of Biofertilizers

Biofertilizers have high nutrient availability in comparison to the conventional fertilizers. Supporting biological N fixation, P solubilization, and increased uptake of micronutrients is supported by N fixing bacteria, Phosphate solubilizing bacteria, and Arbuscular mycorrhizal fungi (Vessey, 2003; Berruti *et al.*, 2016)^[45, 6]. Trials with combined biofertilizer and 50 per cent reduced mineral fertilizer doses in mulberry showed 10-15 per cent increases in leaf biomass and 8-12 per cent improvement in leaf protein content, highlighting their efficacy in sustainable nutrient management (Adesemoye and Kloepper, 2009)^[1].

3.6 Site-Specific Nutrient Budgeting

Effective INM should consider the soil type, frequency of leaf harvest and intensity of irrigation. High rainfall or sandy texture tropical fields are ideal areas that can be pre-monsoon incorporated with organic materials to minimize the loss of nutrients (Vanlauwe *et al.*, 2010)^[44]. According to nutrient budgeting systems, it is preferable to replace 25-50 per cent of the chemical N, 20-30 per cent of P, and 40-50 per cent of K with organic residues to get a stable yield and enhance health of the soil (Choudhury *et al.*, 2020)^[11].

4. Recycling Sericulture Waste: Composting, Vermicomposting, and Digestate Utilization

4.1 Sericulture Waste Streams

Tropical mulberry-based sericulture generates substantial organic residues, including silkworm litter, mulberry pruning's, rejected cocoons, and reeling sludge. Silkworm litter alone accounts for 8-10 MT ha⁻¹ yr⁻¹ dry weight, containing 1.5-3.0 per cent N, 0.8-1.2 per cent P, and 1.2-2.5 per cent K, while mulberry pruning's contribute 5-7 MT ha⁻¹ yr⁻¹ with comparable nutrient content (Sannappa *et al.*, 2012)^[32]. Efficient recycling of these residues is critical for closing nutrient loops, reducing dependence on external fertilizers, and maintaining soil health in high-intensity tropical systems. The major sericulture residues generated in mulberry-based production systems and their typical nutrient composition are summarized in Table 2.

Table 2: Nutrient Composition of Major Sericulture Residues

Residue Type	Annual Availability (MT ha ⁻¹ yr ⁻¹)	Nitrogen (%)	Phosphorus (%)	Potassium (%)	References
Silkworm litter	8-10	1.5-3.0	0.8-1.2	1.2-2.5	Sannappa <i>et al.</i> , 2012 ^[32]
Mulberry pruning residues	5-7	1.2-2.0	0.6-1.0	1.0-2.0	Sannappa & Manjunath, 2013 ^[33]
Vermicompost from sericulture waste	3-5	2.0-3.5	1.0-1.5	1.5-2.2	Lazcano & Domínguez, 2011 ^[24]
Digestate from anaerobic digestion	4-6	1.5-2.5	0.8-1.0	1.0-1.5	Möller & Müller, 2012 ^[27]

4.2 Composting of Sericulture Residues

Composting is the most widely adopted method for stabilizing organic residues. Aerobic composting of silkworm litter and pruning's reduces initial C:N ratios of 20:30 to 12:18 within 60-90 days under tropical temperatures, stabilizing nutrients and improving soil fertility (Bernal *et al.*, 2009)^[5]. Thermophilic phases (55-65 °C) suppress pathogens and accelerate

humification. Application of 5-7 MT ha⁻¹ composted sericulture waste can supply up to 40-50 per cent of annual N demand, enhance soil organic carbon by 15-30 per cent, and improve microbial biomass carbon by 20-40 per cent (Choudhury *et al.*, 2020)^[11]. Compost incorporation before monsoon reduces nutrient runoff and improves aggregate stability by 15-25 per cent.

4.3 Vermicomposting: Accelerated Bioconversion

Vermicomposting, mediated by *Eisenia fetida*, provides rapid nutrient-rich organic matter with enhanced microbial activity. Nitrogen content in vermicompost typically ranges from 2.0-3.5 per cent, higher than conventional compost (Lazcano and Domínguez, 2011) [24]. The process also increases enzymatic activity, producing humic substances that improve CEC and nutrient retention. Application of 5 MT ha⁻¹ vermicompost has been associated with 15-25 per cent improvements in mulberry leaf yield and higher crude protein content (Sannappa and Manjunath, 2013) [33]. Vermicompost further enhances K and micronutrient availability, critical for leaf quality and silkworm nutrition.

4.4 Digestate from Anaerobic Digestion

Anaerobic digestion of sericulture residues produces biogas and nutrient-rich digestate. Digestate contains readily mineralizable N (NH₄⁺-N), and its application at 4-6 MT ha⁻¹ can replace 20-40 per cent of chemical N requirements (Möller and Müller, 2012; Tambone *et al.* 2010) [27, 42]. Digestate must be managed carefully to minimize ammonia volatilization under tropical conditions. When applied judiciously, digestate not only recycles nutrients but also contributes to renewable energy production and reduces greenhouse gas emissions associated with chemical fertilizers.

4.5 Strategic Nutrient Recycling

Recycling sericulture residues aligns with circular bioeconomy principles, enhances soil carbon sequestration, and reduces reactive nitrogen losses. Integration of composting, vermicomposting, and digestate application in a site-specific manner allows partial substitution of mineral fertilizers up to 25-50 per cent N, 20-30 per cent P, and 40-50 per cent K without yield penalties (Choudhury *et al.*, 2020) [11]. The selection of recycling method depends on farm size, labour availability, and infrastructure, with smallholders favouring decentralized composting and vermicomposting, whereas clustered farms may utilize digesters for combined nutrient recovery and energy production (Kalaiyaran *et al.*, 2015) [19].

5. Effects of INM on Soil Physical and Chemical Properties

5.1 Improvement in Soil Structure and Aggregation

INM enhances soil physical properties by restoring organic matter and improving aggregate stability. In tropical mulberry systems, long-term field trials report increases in water-stable aggregates by 15-30 per cent following combined application of composted sericulture residues and mineral fertilizers (Blanco-Canqui and Lal, 2004) [8]. Soil bulk density decreases by 0.05-0.12 MT m⁻³ due to enhanced aggregation and porosity, facilitating root penetration and aeration (Srinivasarao *et al.*, 2014) [40]. The repeated incorporation of organic residues increases macroaggregate formation, which protects soil against erosion during intense monsoon rainfall exceeding 50 mm per day (Lal, 2003) [21].

5.2 Enhancement of Soil Water Retention

INM improves soil water dynamics by increasing soil organic carbon (SOC), which acts as a hydrophilic binding matrix. Tropical soils receiving 5-7 MT ha⁻¹ compost or vermicompost demonstrate 1-3 per cent (w/w) increases in water holding capacity, buffering mulberry crops against short dry spells and intermittent irrigation gaps (Minasny and McBratney, 2018; Srinivasarao *et al.*, 2014) [26, 40]. Improved infiltration reduces runoff and nutrient losses, maintaining effective soil moisture

for continuous leaf harvest.

5.3 Cation Exchange Capacity and Nutrient Retention

Sustained application of humified organic matter under INM increases CEC by 1-3 cmol(+) kg⁻¹ in highly weathered tropical soils (Srinivasarao *et al.* 2014) [40]. This improves retention of NH₄⁺, K⁺, Ca²⁺, and MT²⁺, reducing leaching losses and enhancing nutrient availability for mulberry (Roy *et al.*, 2006) [31]. Enhanced CEC also stabilizes soil pH, counteracting acidification from repeated ammonium-based fertilizer application (Haynes and Naidu, 1998) [15]. INM maintains soil pH within the optimal range of 6.0-7.0, improving nutrient solubility and reducing risks of micronutrient deficiencies.

5.4 Nutrient Stratification Control

Organic amendments under INM improve vertical nutrient distribution in the soil profile. Enhanced aggregate stability reduces preferential flow pathways during irrigation or heavy rainfall, lowering nutrient leaching and improving synchrony between nutrient supply and crop uptake (Srinivasarao *et al.*, 2014) [40]. This is particularly critical for potassium (K⁺) and phosphorus (P), which are susceptible to downward movement and fixation in tropical Alfisols and Inceptisols.

6. Effects of INM on Soil Biological Properties and Nutrient Cycling

6.1 Enhancement of Microbial Biomass

INM enhances soil microbial biomass carbon (MBC), a key indicator of active soil organic matter. Tropical field trials show 20-45 per cent increases in MBC when organic amendments are combined with mineral fertilizers compared with sole inorganic treatments (Fließbach *et al.*, 2007; Zhang *et al.*, 2016) [14, 48]. Higher microbial biomass supports continuous nutrient release across multiple mulberry harvest cycles and reduces N losses through temporary immobilization.

6.2 Stimulation of Soil Enzymes

Organic inputs stimulate key soil enzymes involved in nutrient cycling, including dehydrogenase, urease, phosphatase, and β-glucosidase (Allison and Vitousek, 2005) [3]. Increased phosphatase activity improves organic phosphorus mineralization, offsetting low recovery efficiency of applied P in strongly weathered tropical soils (Sharma *et al.*, 2013) [34]. Elevated enzyme activity reflects enhanced microbial functional diversity and accelerated nutrient turnover.

6.3 Promotion of Symbiotic Associations

Arbuscular mycorrhizal fungi abundance and root colonization are improved under INM, whereas overuse of mineral fertilizers can suppress these associations (Berruti *et al.*, 2016) [6]. Mycorrhizal networks increase root surface area, enhance phosphorus and micronutrient uptake, and improve plant resilience to water stress, particularly in light-textured tropical soils with low inherent fertility.

6.4 Regulation of Nitrogen Cycling

INM improves N cycling by balancing microbial immobilization and mineralization. Adequate organic inputs allow microbes to temporarily immobilize mineral N during periods of low plant uptake, reducing nitrate leaching and nitrous oxide emissions (Kuzakov and Xu, 2013) [20]. Nitrogen-fixing bacteria such as *Azotobacter* and *Azospirillum* further supplement N availability, improving fertilizer efficiency by 8-15 per cent (Adesemoye *et al.*, 2009) [2].

6.5 Enhancement of Microbial Diversity and Soil Stability

Integrated systems foster higher microbial diversity and functional redundancy, improving soil ecosystem stability under climatic variability (Wagg *et al.*, 2014) [47]. A diverse microbial community supports multiple nutrient transformation pathways, including nitrification, denitrification, and biological N fixation, ensuring continuous nutrient supply for high-frequency mulberry harvests.

7. Effects of INM on Mulberry and Silkworm Performance

7.1 Influence on Mulberry Leaf Yield

INM significantly enhances mulberry leaf production by optimizing nutrient availability and synchronizing release with crop demand. Studies in tropical mulberry systems report 12-25 per cent increases in leaf yield when chemical fertilizers are partially substituted (25-50% N) with composted sericulture residues or vermicompost (Choudhury *et al.*, 2020; Sannappa *et al.*, 2012) [11, 32]. Leaf biomass typically ranges from 18-22 MT ha⁻¹ yr⁻¹ under INM, compared with 15-18 MT ha⁻¹ yr⁻¹ under sole chemical fertilization. Enhanced yields are attributed to improved soil structure, higher microbial biomass, and better nutrient retention (Zhang *et al.* 2016) [48].

7.2 Improvements in Leaf Biochemical Quality

Leaf protein content, chlorophyll concentration, and amino acid profile are critical determinants of silkworm growth. INM treatments maintain leaf crude protein at 20-24 per cent dry weight, compared with 16-18 per cent under chemical-only regimes (Reddy *et al.*, 2013) [30]. Potassium-rich organic amendments improve phloem loading and soluble sugar content, enhancing carbohydrate translocation to leaves (Zorb *et al.*, 2014) [51]. Micronutrient availability, including Fe, Zn, and Mn, is elevated under INM, improving enzymatic functions and leaf metabolic efficiency (Cakmak and Kutman, 2018) [10].

7.3 Silkworm Growth and Cocoon Performance

Enhanced leaf quality under INM translates to improved silkworm performance. Studies report 8-15 per cent higher larval weight and 5-12 per cent greater cocoon shell weight when larvae are fed leaves from integrated nutrient plots (Singh *et al.*, 2012) [36]. Improved digestibility and amino acid balance reduce larval mortality and increase feed conversion efficiency. Multi-harvest systems benefit particularly, as nutrient release from organic amendments ensures consistent leaf quality across 5-6 annual harvests (Ashaq *et al.*, 2025) [4].

7.4 Physiological and Agronomic Mechanisms

INM stabilizes soil moisture through increased organic carbon, moderating water stress during dry spells common in tropical climates (Minasny and McBratney, 2018) [26]. Optimized nitrogen availability promotes chlorophyll synthesis and photosynthetic efficiency, while balanced K supports stomatal regulation, enhancing carbon assimilation and leaf growth (Taiz *et al.*, 2015) [41]. arbuscular mycorrhizal fungi, phosphate solubilizing bacteria colonization and microbial diversity under INM improve nutrient uptake efficiency, further contributing to leaf yield and quality (Berruti *et al.*, 2016; Adesemoye and Kloepper, 2009) [6, 1].

INM not only increases leaf yield by up to 25 per cent but also improves protein, carbohydrate, and micronutrient content, translating to measurable gains in silkworm growth and silk quality. The integration of organic and inorganic inputs ensures both short-term productivity and long-term soil fertility in tropical mulberry systems.

8. Environmental Sustainability and Climate Resilience under INM

8.1 Reduction of Reactive Nitrogen Losses

INM mitigates environmental risks by improving nitrogen use efficiency and reducing reactive nitrogen losses. In tropical mulberry systems, nitrate leaching under sole chemical fertilization can reach 30-50 per cent of applied N due to high rainfall and sandy soil textures (Zhang *et al.* 2016) [48]. Partial substitution of mineral N with composted sericulture residues or vermicompost reduces nitrate leaching by 15-25 per cent through microbial immobilization and gradual mineralization (Adesemoye *et al.*, 2009) [2]. INM also lowers nitrous oxide (N₂O) emissions, which account for 1-2 per cent of applied N under conventional management, by stabilizing ammonium and nitrate pools in the soil (Shcherbak *et al.*, 2014; Zhang *et al.*, 2012) [35, 49].

8.2 Soil Carbon Sequestration

INM enhances soil organic carbon (SOC) stocks through repeated incorporation of organic residues. Long-term field studies in tropical perennial systems report annual SOC increases of 0.3-0.6 MT C ha⁻¹ yr⁻¹ when 5-7 MT ha⁻¹ of compost or vermicompost is applied (Powlson *et al.*, 2011; Lal, 2016) [29, 23]. SOC enrichment improves aggregate stability by 15-30 per cent, reduces erosion under monsoonal rainfall, and protects organic carbon from rapid mineralization in warm, humid soils (Blanco-Canqui and Lal, 2004; Lal, 2003) [8, 21]. Enhanced SOC also strengthens CEC, water retention, and nutrient buffering, creating resilience against climatic extremes.

8.3 Mitigation of Greenhouse Gas Emissions

Partial replacement of synthetic Nitrogen fertilizers with recycled organic residues decreases the energy footprint of mulberry cultivation. Synthetic N production consumes 35-60 MJ kg⁻¹ N and contributes to significant CO₂-equivalent emissions (International Fertilizer Association [IFA], 2009; Snyder *et al.*, 2009) [17, 39]. By supplying 25-50 per cent of N requirements through composted residues or digestate, INM reduces embedded emissions and aligns tropical sericulture with climate-smart agriculture objectives (Lal, 2016) [23].

8.4 Climate Resilience and Water Buffering

Organic matter additions under INM improve soil water holding capacity by 1-3 per cent (w/w), depending on texture, mitigating short-term drought stress (Minasny and McBratney, 2018) [26]. Enhanced aggregation reduces surface crusting and runoff, preserving nutrients during intense rainfall events exceeding 50 mm per day. Improved root penetration and microbial activity foster physiological resilience, allowing mulberry to maintain stable leaf yield under variable rainfall and temperature fluctuations (Zhang *et al.*, 2016; Lal, 2015) [48, 22].

INM in tropical mulberry systems strengthens both mitigation and adaptation pathways. By reducing nitrate leaching, nitrous oxide emissions, and fossil energy consumption, while simultaneously increasing SOC, water retention, and structural stability, INM integrates environmental sustainability with climate resilience. This positions mulberry cultivation as a model for climate-smart tropical agriculture.

9. Economic Feasibility, Adoption Constraints, and Policy Implications

9.1 Economic Viability of INM

INM offers measurable economic benefits by reducing dependence on costly synthetic fertilizers. In irrigated tropical

mulberry gardens, nitrogen application rates often exceed 250 kg ha⁻¹ yr⁻¹, representing 25-35 per cent of total cultivation costs (Food and Agriculture Organization [FAO], 2022; Choudhury *et al.*, 2020) ^[13, 11]. Partial substitution (25-50% N) with composted silkworm litter or vermicompost reduces fertilizer expenditure while maintaining or increasing leaf yields by 10-25 per cent (Sannappa *et al.*, 2012; Zhang *et al.* 2016) ^[32, 48]. Economic analyses indicate that benefit-cost ratios improve by 10-20 per cent under INM compared with sole chemical fertilization.

9.2 Labor and Infrastructure Considerations

Adoption of INM requires additional labour and infrastructure for composting, vermicomposting, or digestate handling. Smallholder households, often managing <1 ha, face seasonal labour shortages due to migration (Binswanger-Mkhize, 2012) ^[7]. Preparing 5-10 MT ha⁻¹ of compost or vermicompost may require 60-80 man-days annually, depending on mechanization level (Kalaiyarasan., 2015) ^[19]. Despite this, labour investment is partially offset by reduced fertilizer handling and lower input costs over multiple harvest cycles.

9.3 Knowledge and Technical Barriers

Successful INM requires understanding nutrient budgeting, residue processing, and timing of application. Variability in compost nutrient content, particularly N, P, and K, can create uncertainty in substitution rates if soil testing is not performed (Choudhury *et al.*, 2020) ^[11]. Farmer training and extension support are therefore critical; evidence shows participatory learning approaches, such as farmer field schools, increase adoption of integrated soil fertility practices by 15-30 per cent compared with passive information dissemination (Waddington *et al.* 2014) ^[46].

9.4 Policy and Institutional Support

Policy mechanisms can accelerate INM adoption in tropical sericulture regions. Government programs such as the Soil Health Card Scheme provide soil testing services and recommendations that enable optimized nutrient management (Government of India, 2022) ^[18]. Subsidies for composting infrastructure, biofertilizer distribution, and demonstration plots reduce initial barriers for smallholders. Integration of INM with climate-smart agriculture initiatives including carbon credit incentives can further enhance adoption, linking economic benefits with environmental stewardship (Lal, 2016) ^[23]. Coordination between sericulture departments, agricultural universities, and farmer cooperatives is essential to standardize nutrient budgeting and improve the quality of recycled residues (Choudhury *et al.*, 2020) ^[11].

INM is economically viable in tropical mulberry systems, improving benefit-cost ratios by reducing fertilizer input costs while maintaining or enhancing yields. Labor and technical knowledge requirements present adoption challenges, particularly for smallholders, but can be mitigated through extension services, training programs, and supportive policies. Targeted subsidies, soil health monitoring, and climate-smart incentives provide a pathway for scaling sustainable nutrient management practices in tropical sericulture clusters.

10. Research gaps and future directions

Despite growing evidence supporting INM in tropical agroecosystems, significant research gaps persist in mulberry-based sericulture systems. Long-term (>10 years) experiments specifically evaluating soil carbon stabilization mechanisms

under mulberry monocropping are limited, particularly in highly weathered Alfisols and Inceptisols common in southern India (Smith *et al.*, 2020) ^[38]. Quantitative assessments of carbon sequestration rates under sericulture residue recycling remain sparse, and region-specific emission factors for nitrous oxide under integrated nutrient regimes are poorly characterized (Tubiello *et al.* 2021). Nutrient budgeting frameworks tailored to multi-harvest perennial systems are underdeveloped, with insufficient modelling of nutrient removal across 5-6 annual leaf harvests. Variability in compost nutrient composition and mineralization kinetics of silkworm litter under tropical temperature regimes also require standardized evaluation (Awasthi *et al.*, 2020). Furthermore, limited research addresses interactions between INM, micronutrient dynamics, and leaf biochemical quality directly affecting silkworm physiology. Socio-economic adoption studies specific to sericulture clusters are comparatively scarce, particularly regarding gender participation, labour dynamics, and risk perception. Integration of soil biological indicators such as microbial functional genes associated with nitrogen cycling into mulberry nutrient management research is also minimal, constraining mechanistic understanding of nutrient transformation pathways.

Future research should prioritize long-term, multi-location trials integrating soil carbon fractionation, greenhouse gas monitoring, and nutrient recovery efficiency in tropical mulberry systems. Development of site-specific nutrient decision-support tools incorporating remote sensing and precision agriculture approaches can enhance fertilizer synchronization. Standardized protocols for compost quality assessment and nutrient mineralization modelling are needed to improve substitution accuracy. Integrating climate-smart agriculture frameworks with sericulture extension programs, alongside life-cycle assessment of fertilizer substitution strategies, will strengthen sustainability evaluation and guide policy formulation for resilient tropical sericulture systems.

11. Conclusion

INM provides a sustainable strategy for enhancing productivity, soil health, and environmental resilience in tropical mulberry-based sericulture systems. In tropical regions, frequent leaf harvesting, high temperatures, and intense rainfall accelerate nutrient cycling and often result in nitrogen losses, phosphorus fixation, potassium depletion, and decline in soil organic carbon. INM addresses these challenges by integrating mineral fertilizers with organic amendments such as composted mulberry pruning's, silkworm litter, vermicompost, digestate, and biofertilizers including nitrogen-fixing bacteria, phosphate-solubilizing microorganisms, and arbuscular mycorrhizal fungi. This integrated approach improves soil physical, chemical, and biological properties. Enhanced aggregate stability, CEC, and water-holding capacity strengthen nutrient retention and reduce leaching losses. Increased microbial biomass and enzymatic activity support efficient nutrient cycling and sustained availability. As a result, mulberry leaf yield can increase by 20-25 per cent, along with improvements in crude protein and carbohydrate content, ensuring consistent leaf quality across multiple harvests. These improvements directly enhance silkworm growth, cocoon shell weight, and silk quality.

Environmentally, INM reduces reactive nitrogen losses, mitigates greenhouse gas emissions, and promotes soil organic carbon sequestration, contributing to climate resilience. Recycling sericulture residues within the production system supports circular nutrient flows and reduces dependence on synthetic fertilizers. Economically, partial substitution of

chemical fertilizers with organic inputs lowers production costs and improves benefit-cost ratios. However, successful adoption requires technical knowledge, labour availability, soil testing support, and effective extension services. Policy incentives and infrastructure development can further facilitate implementation among smallholders. INM integrates agronomic efficiency, ecological sustainability, and socio-economic feasibility, offering a climate-smart model for resilient and productive tropical sericulture systems.

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