



International Journal of Research in Agronomy

E-ISSN: 2618-0618
P-ISSN: 2618-060X
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NAAS Rating (2026): 5.20
www.agronomyjournals.com
2026; SP-9(7): 389-397
Received: 20-04-2026
Accepted: 22-05-2026

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Controlled environment sericulture: Opportunities for vertical farming and indoor mulberry production toward sustainable silk systems

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DOI: <https://www.doi.org/10.33545/2618060X.2026.v9.i7Se.6119>

Abstract

Sericulture supports the livelihoods of millions of rural households across Asia, yet conventional mulberry (*Morus* spp.) cultivation remains heavily dependent on open-field conditions, seasonal rainfall, and extensive land area, leaving the sector exposed to climate variability, water scarcity, and pest pressure. Controlled environment agriculture (CEA), comprising greenhouse systems, vertical farms, plant factories with artificial lighting, and soilless cultivation methods such as hydroponics and aeroponics, has reshaped production of leafy vegetables and other high-value horticultural crops, but its application to mulberry and silkworm-based silk production remains almost entirely unexamined in the scientific literature. This review brings together evidence from plant factory horticulture, soilless mulberry propagation trials, sericulture physiology, and precision agriculture to assess whether controlled environment principles can reasonably be transferred to mulberry cultivation and, by extension, to silkworm rearing. We examine mulberry's physiological suitability for indoor, multi-tier production; the comparative performance of nutrient film, deep-water culture, and aeroponic systems; the influence of LED spectral quality on mulberry leaf biochemistry; and the environmental control parameters that plant factories already manage for other leafy crops. We further consider Internet of Things based monitoring, year-round rearing potential, water and land use implications, the economic barriers tied to energy cost, and the considerable research gaps that currently separate horticultural plant factory science from sericulture practice. The review concludes that controlled environment sericulture is technically plausible and supported by isolated proof-of-concept findings on mulberry, but requires dedicated agronomic, entomological, and engineering research before commercial adoption can reasonably be considered.

Keywords: Controlled environment agriculture, vertical farming, mulberry (*Morus* spp.), sericulture, silkworm rearing, soilless cultivation, LED lighting, plant factory, precision agriculture, sustainable silk production

1. Introduction

Sericulture, the integrated practice of mulberry cultivation and silkworm rearing for raw silk production, remains one of the most labour-intensive branches of agriculture and supports millions of rural livelihoods across the major producing countries^[10]. Mulberry-based silk dominates global output, with China and India together accounting for the large majority of world production; the silk sector is reported to employ approximately one million workers in China and around 7.9 million people in India^[10]. Yet the entire value chain rests on a single biological constraint: *Bombyx mori* L. is a monophagous insect that feeds exclusively on mulberry leaf, so the quantity, continuity, and nutritional composition of that leaf supply set the upper limit on cocoon yield and silk quality^[14].

Mulberry leaf quality, governed by leaf age, moisture content, and the balance of protein, carbohydrate, and micronutrient content, directly affects larval growth rate, cocoon weight, shell ratio, and ultimately filament quality. Decades of sericulture physiology research have established that even modest deficiencies in leaf nutrition translate into measurable losses in rearing performance^[14]. Because leaf quality is itself shaped by the growing environment, temperature, humidity, soil moisture, and seasonal light availability, conventional open-field

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mulberry cultivation transmits the variability of weather directly into the silk production system rather than buffering against it.

This dependence on open-field conditions is becoming a more serious constraint as climate pressures intensify. Reviews of climate change impacts on sericulture report that rising temperature and erratic rainfall reduce mulberry leaf yield and nutritional quality while simultaneously imposing physiological stress on silkworms, lowering cocoon survival and quality. Above-ambient carbon dioxide concentration has been shown to partially offset drought-induced losses in mulberry biomass production under controlled growth-chamber conditions, raising leaf and root biomass by more than one-third relative to ambient conditions during severe water stress ^[15], a finding that itself depends on the kind of environmental control that open-field cultivation cannot offer. Land competition from urban expansion, recurring water scarcity in major sericulture-producing states, and seasonal pest and disease outbreaks add further pressure on a system that remains, at present, almost entirely weather-exposed.

Controlled environment agriculture (CEA) offers one route around these constraints. CEA covers a spectrum of production systems, from passively ventilated greenhouses to fully enclosed, multi-tier plant factories with artificial lighting, unified by the principle that key growth variables, including temperature, humidity, carbon dioxide concentration, nutrient supply, and light, are deliberately regulated rather than left to ambient conditions ^[8, 16]. Vertical farming, in which crops are stacked in multiple horizontal layers within a building rather than spread across a single field plane, is the most land-efficient expression of this principle and has already been demonstrated at commercial scale for lettuce, herbs, and other fast-cycling leafy crops ^[8, 13]. The same underlying technologies, soilless nutrient delivery, LED spectral control, and automated climate management, are increasingly proposed as tools for crops well beyond the vegetable sector for which they were first developed. Despite this momentum, the application of CEA principles to mulberry cultivation, and by extension to the silkworm rearing that depends on it, remains close to undocumented in the scientific literature. A recent status review identified mulberry as a strong physiological candidate for vertical farming on account of its rapid growth and adaptability to hydroponic, aeroponic, and aquaponic systems, while explicitly noting that supporting research is still at an early, exploratory stage ^[2]. This review draws together that limited but suggestive body of mulberry-specific evidence with the considerably larger literature on plant factory horticulture, soilless cultivation engineering, and sericulture physiology, in order to ask three connected questions: whether mulberry is agronomically suited to indoor, multi-tier cultivation; how such cultivation might be expected to affect silkworm rearing outcomes; and what research, engineering, and economic barriers separate current proof-of-concept findings from a functioning controlled environment sericulture system. In doing so, the review treats controlled environment sericulture not as an established technology but as a clearly bounded, currently underexplored research direction, and sets out the steps that would be needed to test it properly.

2. Overview of controlled environment agriculture

Controlled environment agriculture refers to any production system in which one or more elements of the growing environment, light, temperature, humidity, carbon dioxide concentration, or root-zone nutrition, are actively managed

rather than determined by outdoor conditions ^[8]. The term spans a wide range of physical structures and levels of technological intensity. At the simpler end, polytunnels and naturally ventilated greenhouses moderate temperature and shield crops from rainfall while still relying substantially on ambient sunlight. At the more intensive end, plant factories with artificial lighting (PFAL) are fully enclosed, insulated structures in which sunlight plays no role and every photon reaching the crop canopy is supplied by LED fixtures on a programmed schedule ^[5, 6]. Vertical farming sits within this spectrum as a spatial strategy rather than a single technology: crops are arranged in stacked horizontal layers, typically serviced by soilless root-zone systems, so that production per unit floor area is multiplied several-fold compared with a single field plane ^[16].

Three soilless approaches recur across the CEA literature and are directly relevant to a discussion of indoor mulberry. Hydroponic systems suspend or circulate plant roots in a nutrient solution rather than soil, most commonly through the nutrient film technique (NFT), in which a thin film of solution flows continuously over the roots, or deep-water culture (DWC), in which roots remain submerged in an aerated reservoir. Comparative trials on lettuce indicate that NFT consistently outperforms DWC on leaf area, fresh yield, and dry yield, an advantage attributed to superior root oxygenation ^[19]. Aeroponic systems dispense with a liquid reservoir altogether, suspending roots in air and delivering nutrients as a fine mist; the approach is reported to support strong root development and reduced root-borne disease pressure, although the misting hardware is mechanically more demanding to maintain than NFT or DWC. Aquaponic systems couple a hydroponic crop component with recirculating aquaculture, using fish effluent as the nutrient source for the plants, which act in turn as a biological filter for the water returned to the fish; the configuration adds a second, sellable output but introduces the additional complexity of maintaining water chemistry suitable for both organisms at once ^[12].

Whichever cultivation method is used, plant factories manage a consistent set of environmental variables. Temperature and relative humidity are held within a narrow, crop-appropriate band using heating, ventilation, and dehumidification equipment; carbon dioxide is frequently enriched above ambient concentration because net photosynthesis in most C3 crops continues to rise with carbon dioxide supply well beyond the roughly 420 parts per million found in outdoor air ^[11, 17]. Nutrient solutions are formulated, monitored, and replenished automatically, with pH and electrical conductivity tracked continuously rather than checked periodically as in field agriculture. Increasingly, this environmental management is coordinated by networked sensors and control software rather than manual adjustment, a development discussed further in Section 7, allowing a single facility to maintain stable conditions across many production tiers simultaneously rather than relying on the judgement of an individual grower walking the crop.

3. Mulberry as a candidate crop for indoor cultivation

Mulberry (*Morus* spp.) is a fast-growing, woody plant cultivated across a wide latitudinal range, from temperate to tropical zones, primarily for its foliage rather than its fruit in sericulture systems ^[2]. Its rapid vegetative growth, propagation by stem cuttings, and tolerance of repeated, severe pruning for leaf harvest are precisely the traits that have historically made it a productive field crop, and the same traits make it a reasonable, if largely

untested, candidate for intensive indoor systems that depend on rapid, repeated biomass turnover rather than a single seasonal harvest.

The case for examining mulberry under controlled conditions follows directly from its role as the sole larval food of *Bombyx mori*. Because leaf protein, carbohydrate, and moisture content determine larval growth rate, cocoon weight, and shell ratio, any cultivation method capable of producing leaf with a more consistent, and potentially improved, nutrient profile has implications extending well beyond plant agronomy into rearing performance^[14]. Indoor systems offer, at least in principle, the ability to separate leaf composition from weather: a grower could adjust light spectrum, nutrient formulation, and water availability specifically to favour the protein content that matters for silkworm nutrition, rather than accepting whatever combination of temperature and rainfall a given week happens to deliver. More broadly, mulberry's bioactive and nutrient composition is already known to vary measurably with growing-site conditions such as altitude, temperature range, and precipitation^[4], a sensitivity consistent with, even if not direct evidence for, the proposition that deliberately controlled growing conditions could be used to shape leaf composition in a targeted way.

The limited direct evidence available is encouraging but narrow in scope. A comparative trial on the Kokuso 21 cultivar propagated from seed in conventional soil beds, an aeroponic system, and *in vitro* tissue culture found that the aeroponic treatment produced the most favourable growth outcomes among the three methods tested, with immediate field applicability, while tissue culture remained useful chiefly for germplasm conservation rather than leaf production^[3]. A separate study comparing soil, vermiculite, and a dynamic root floating hydroponic technique for mulberry transplants found that the micro-environment at the root and shoot zone, combined with LED spectral quality, significantly altered both survival rate and the concentration of bioactive leaf compounds, with blue light specifically inducing higher phenolic accumulation^[18]. Neither study was designed around sericulture outcomes, but together they demonstrate that mulberry responds measurably, and in some cases favourably, to the specific cultivation variables that controlled environment systems are built to manipulate.

Biomass production and leaf regeneration capacity are particularly relevant given the heavy, repeated defoliation that sericulture leaf harvest demands. Independent of the indoor cultivation question, mulberry's capacity to increase whole-plant biomass under above-ambient carbon dioxide, including during drought stress, has been documented under controlled growth-chamber conditions, with leaf and root biomass increases approaching one-third relative to ambient carbon dioxide during severe water stress^[15]. While these chamber trials were conducted for physiological rather than production purposes, they confirm that mulberry's biomass response is sensitive to exactly the kind of carbon dioxide management that plant factories already practise routinely for other crops, reinforcing the agronomic plausibility, even if not yet the commercial proof, of indoor mulberry production.

4. Vertical farming approaches for mulberry production

Translating the proof-of-concept findings described in Section 3 into a defined production system requires choosing among the

soilless approaches summarised in Table 1. Nutrient film technique and deep-water culture, the two dominant hydroponic configurations in commercial leafy-crop plant factories, have not yet been compared directly on mulberry, but their relative performance on other species, NFT consistently outperforming DWC on yield and quality indices, gives a reasonable starting hypothesis for early-stage trials^[19]. Both systems would need adaptation for a woody perennial: standard NFT channels are shallow and designed for short-rooted annual leafy crops, so a mulberry-adapted configuration would likely need wider channels, greater allowance for root volume, and a harvesting regime built around repeated cutting back rather than single-pass removal of the whole plant.

Aeroponic cultivation is, on current evidence, the more promising of the two soilless routes specifically for mulberry. Misting roots with nutrient solution, rather than immersing them in or flowing solution past them, gives the strongest aeration of the root zone among soilless methods, an advantage that the available mulberry trial found translated into the best overall growth outcome among the soil, aeroponic, and tissue-culture treatments tested^[3]. The same root aeration is reported to reduce the incidence of root-borne disease in other crops, which would be a relevant secondary benefit for sericulture facilities, where leaf hygiene already matters for downstream silkworm health. Root-zone temperature management, increasingly studied in NFT and aeroponic lettuce systems, is a further variable that has not yet been examined in mulberry but represents a plausible refinement once basic aeroponic protocols are established^[7].

Substrate-based systems, in which plants are grown in an inert, soilless medium such as rockwool, coir, or perlite irrigated with nutrient solution, occupy a middle position between conventional pot or field cultivation and fully liquid hydroponic systems. For a woody, repeatedly pollarded crop such as mulberry, a substrate system may offer a practical advantage over NFT or DWC, namely greater root anchorage for a crop subject to frequent above-ground biomass removal, without sacrificing the principal benefits of soilless production, controlled nutrient delivery and reduced soil-borne pest and pathogen pressure. Multi-tier vertical arrangement, regardless of which soilless method is chosen at the root zone, is what converts any of these systems from a space-neutral alternative to conventional cultivation into a genuinely land-efficient one, since stacking several growing layers within the same floor footprint multiplies leaf output per unit of building area.

Set against open-field mulberry cultivation, the directional advantages claimed for vertical, soilless systems in the wider CEA literature, substantially reduced water use through closed-loop nutrient recirculation, multiplied yield per unit land area through vertical stacking, and reduced reliance on field-applied pesticides because the growing environment is physically enclosed, would, if they transfer to mulberry, address several of the structural vulnerabilities identified in Section 1^[13, 16]. None of these advantages has yet been measured for mulberry specifically under commercial-scale conditions, and the energy cost required to sustain them, discussed in Sections 9 and 10, is a substantial qualification rather than a footnote. The comparison set out in Table 1 should therefore be read as an account of what soilless systems are reported to deliver for leafy crops in general, alongside the much thinner evidence available for mulberry in particular, rather than as a settled verdict on indoor mulberry economics.

Table 1: Soilless cultivation systems relevant to indoor mulberry production

System	Operating principle	Reported advantages	Reported limitations
Nutrient film technique (NFT)	Thin film of nutrient solution flows continuously over roots in a shallow channel	Water-efficient; good root oxygenation; outperformed DWC on yield and quality in lettuce trials	Sensitive to pump or flow interruption; restricted root volume for woody cuttings
Deep-water culture (DWC)	Roots fully submerged in an aerated nutrient reservoir	Simple design; buffered nutrient supply; tolerant of short power interruptions	Generally lower yield and photosynthetic performance than NFT in comparative trials
Aeroponic	Roots suspended in air, intermittently misted with nutrient solution	Best growth outcome among soil, aeroponic, and tissue-culture treatments tested specifically on mulberry; strong root aeration; reduced root-borne disease pressure	Technically demanding misting control; nozzle clogging risk; not yet validated at production scale for mulberry
Aquaponic	Hydroponic crop component coupled with recirculating aquaculture	Nutrient recycling from fish effluent; dual-output system (crop and fish)	Added complexity of biofilter and water-chemistry management; not yet tested with mulberry

Note: DWC, deep-water culture; NFT, nutrient film technique. Advantages and limitations are drawn from the wider soilless-cultivation literature except where the cited evidence is specific to mulberry

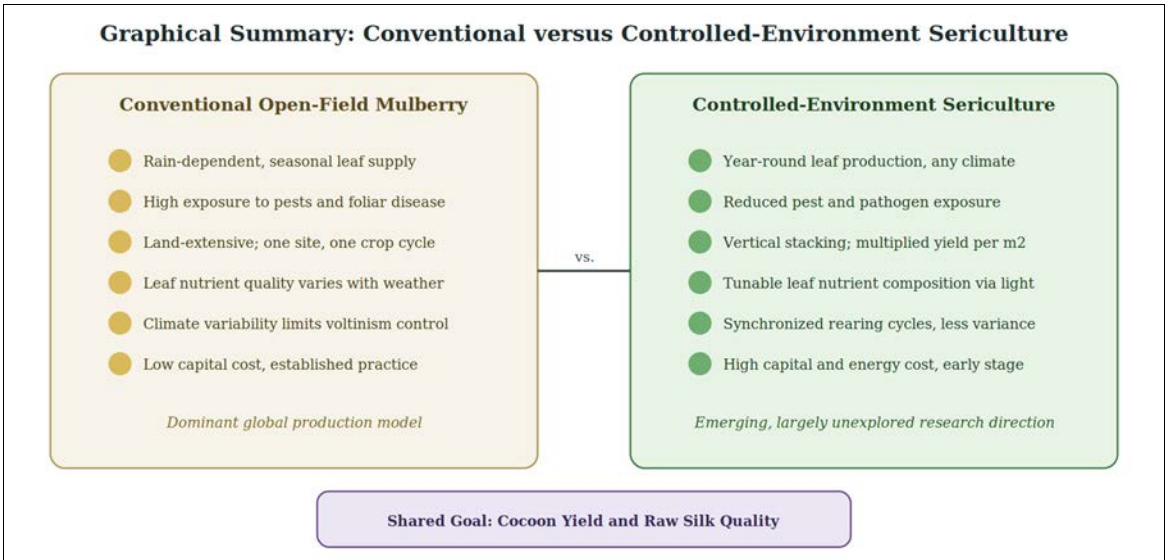


Fig 1: Graphical Abstract. Conventional open-field mulberry cultivation compared with controlled-environment sericulture, sharing the same downstream goal of cocoon yield and raw silk quality

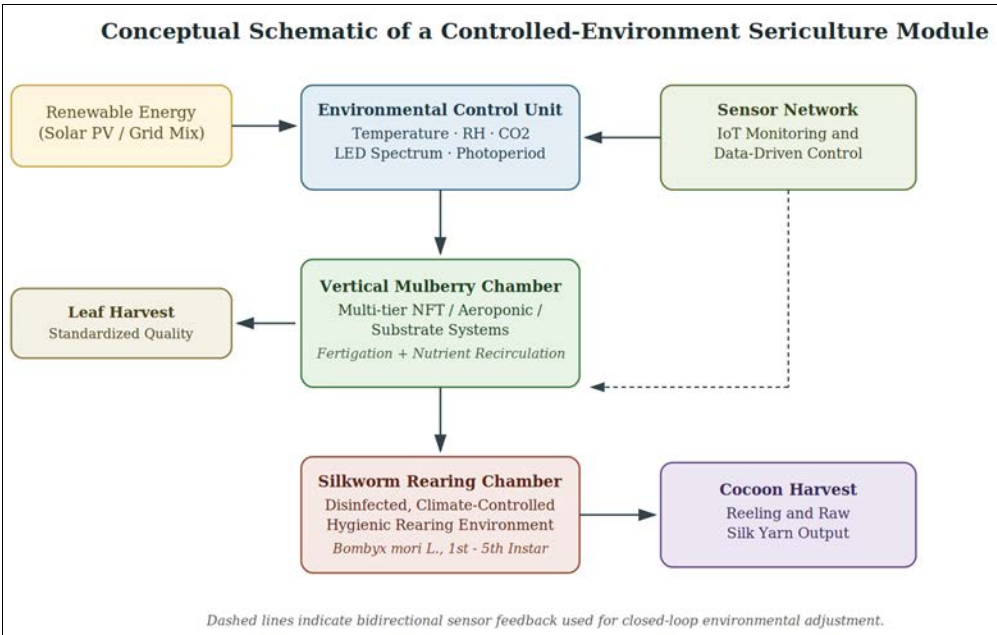


Fig 2: Conceptual schematic of a controlled-environment sericulture module, linking environmental control, sensor monitoring, vertical mulberry production, leaf harvest, and silkworm rearing within a single managed facility.

5. Artificial lighting and environmental control

In a fully enclosed plant factory, light is not a background condition but an engineered input, defined by its intensity (photosynthetic photon flux density), spectral composition, and daily duration (photoperiod), each of which can be set independently of the others and adjusted across the crop cycle.

This degree of control is what distinguishes PFAL systems most clearly from greenhouses, where natural daylight still supplies most or all of the photosynthetically active radiation, and it is also the single largest driver of plant factory electricity consumption, a tension returned to in Section 9 [5, 6].

Light-emitting diode fixtures have become the standard light source for plant factories because individual diode colours can be combined to produce a spectrum tailored to a particular crop response, rather than the fixed, broad-spectrum output of older fluorescent or high-pressure sodium lamps. Across a range of leafy vegetables, red and blue wavebands are reported to govern most of the relevant physiological responses: red light generally drives the highest growth rate and photosynthetic output, while blue light favours a more compact growth habit and tends to raise phenolic and antioxidant content, often at some cost to total biomass [5, 6]. Where these two wavebands are combined, the resulting red-to-blue ratio becomes itself a design variable, with different ratios reported to favour yield, nutrient content, or visual quality depending on the species and the grower's priority [6].

For mulberry specifically, the limited evidence available points in the same general direction as the broader leafy-crop literature, with the qualification that mulberry is grown as silkworm feed rather than for direct human consumption, so the target outcome is leaf protein and digestibility rather than consumer-facing nutritional traits. Blue LED light at 445 nanometres has been shown to increase total phenolic accumulation in mulberry transplant leaves, while broader-spectrum white LED light favoured total protein, soluble sugar, and overall biomass

accumulation in the same trial [18]. Because protein content is one of the leaf traits most directly linked to silkworm larval growth and cocoon quality [14], this finding suggests that a white-light-dominant or balanced-spectrum regime, rather than a strongly blue-shifted one of the kind sometimes favoured for human-consumed leafy greens, would be the more defensible starting point for mulberry grown as silkworm feed. This remains an inference drawn from a single transplant-stage study, however, rather than an established cultivation recommendation. Temperature, relative humidity, and carbon dioxide concentration are managed alongside light rather than independently of it, because photosynthetic response to carbon dioxide enrichment depends on adequate light supply, and transpiration, and therefore humidity management, scales with both light intensity and temperature. Carbon dioxide enrichment to roughly 600 to 1, 000 parts per million is reported to raise net photosynthesis substantially above ambient-air values across a wide range of C3 crops, with the response strongest precisely when light and other resources are otherwise limiting [11, 17]. Mulberry's own response to above-ambient carbon dioxide, documented in growth-chamber rather than plant-factory conditions, follows the same qualitative pattern, with the largest relative biomass gains observed under drought stress rather than under already favourable water availability [15]. Translating any of these parameters into an operating protocol for a working indoor mulberry facility, rather than a controlled laboratory chamber, is one of the clearer near-term research tasks identified in Section 11.

Table 2: Indicative environmental control parameters reported for leafy-crop plant factories and their documented or inferred relevance to indoor mulberry production

Parameter	Commonly reported range for leafy-crop plant factories	Relevance to mulberry / sericulture
Air temperature	Maintained within a narrow, crop-appropriate band by heating, ventilation, and cooling equipment	No dedicated mulberry plant-factory protocol published; growth-chamber trials use controlled day and night temperatures
Relative humidity	Actively dehumidified or humidified to limit disease pressure and manage transpiration	Directly relevant to downstream silkworm rearing-house hygiene if leaf is supplied without field-acquired moisture contamination
Carbon dioxide	Enriched to approximately 600-1, 000 ppm to raise net photosynthesis above ambient-air values	Above-ambient carbon dioxide raised mulberry leaf and root biomass by up to about one-third under drought stress in growth-chamber trials
Light spectrum	Red-blue LED combinations widely used; ratio adjusted for growth rate versus phenolic and antioxidant content	Blue light (445 nm) raised phenolic content in mulberry transplant leaves; white light favoured protein and biomass accumulation
Photoperiod	Typically 12-16 hours per day in commercial PFAL operation	Continuous, year-round mulberry leaf production without winter dormancy has been pursued in patent-described hydroponic systems

Note: ppm, parts per million; PFAL, plant factory with artificial lighting. Values for leafy crops are drawn from the general plant-factory literature; mulberry-specific entries are drawn from the limited dedicated studies identified in this review and should be treated as preliminary.

6. Implications for silkworm rearing and silk production

Everything described in the preceding three sections matters to sericulture only to the extent that it changes what reaches the silkworm. Larval growth rate, fifth-instar weight, cocoon weight, shell weight, and shell ratio are all sensitive to leaf nutritional quality, and seasonal and varietal differences in leaf composition are already established drivers of measurable differences in these traits under conventional field rearing [14]. A controlled environment system that produced leaf with a more stable, and ideally improved, protein and moisture profile across the year would be expected, by direct extension of this established relationship, to reduce the season-to-season variability in rearing outcomes that is currently an accepted feature of field-based sericulture, even though no published study has yet measured this directly using indoor-grown leaf.

Year-round rearing is the most immediately attractive implication of indoor mulberry production, since it removes the defoliation and dormancy constraint that limits conventional cultivation to a defined growing season in most producing

regions. A patented design for a movable, LED-illuminated hydroponic mulberry system describes continuous lighting and temperature management that keep mulberry in continuous vegetative growth without the winter dormancy that field-grown trees undergo, producing leaf even in winter months when field supply is normally unavailable [20]. While patent documentation is not equivalent to peer-reviewed evidence of rearing outcomes, it confirms that the underlying horticultural objective, continuous leaf availability independent of season, has already been pursued as an engineering problem rather than remaining purely theoretical.

Hygiene and disease reduction represent a second plausible benefit, grounded less in mulberry agronomy than in the well-established relationship between rearing-house cleanliness and silkworm disease incidence. Major silkworm diseases, including nuclear polyhedrosis, flacherie, and muscardine, are transmitted predominantly through contaminated leaf, faecal matter, and rearing-house surfaces, and standard management practice already centres on rigorous disinfection and the avoidance of

damp, contaminated leaf ^[14]. An enclosed cultivation facility, physically separated from open-field pest and pathogen sources and capable of supplying leaf without exposure to rain-driven fungal contamination, would in principle remove one transmission route into the rearing house, though this remains an extension of known disease epidemiology rather than a finding specific to controlled environment sericulture, since no study has yet compared disease incidence between conventionally and indoor-sourced leaf under matched rearing conditions.

Taken together, the plausible productivity gains, more consistent leaf nutrition, continuous year-round availability, and reduced exposure to certain disease vectors, would address some of the most persistent sources of variability in sericulture output. The honest position, consistent with the limited direct evidence reviewed in Sections 3 to 5, is that these are reasoned extrapolations from established sericulture physiology and from CEA performance in other crops, not yet demonstrated outcomes of an operating controlled environment sericulture facility. Closing that gap, with rearing trials that compare conventionally grown and indoor-grown leaf under otherwise identical conditions, is among the most direct and tractable research priorities to follow from this review.

7. Smart technologies in controlled environment sericulture

Internet of Things (IoT) infrastructure, networks of low-cost sensors reporting temperature, humidity, light, and nutrient solution parameters to a central control system, has become close to a default feature of commercial plant factories, allowing a single operator to supervise conditions across many production tiers without constant manual measurement. Systematic reviews of IoT adoption in agriculture describe consistent gains in irrigation precision, earlier detection of developing stress conditions, and reduced labour requirement for routine monitoring tasks, alongside persistent challenges around sensor reliability, data standardisation, and deployment cost for smaller operators. None of this literature addresses sericulture facilities specifically, but the underlying sensing and control problem, maintaining stable temperature, humidity, and nutrient conditions across a multi-tier indoor crop, is identical to the one a controlled environment mulberry system would need to solve.

Artificial intelligence and machine learning applications layered on top of this sensor infrastructure are reviewed for vertical farming in the form of automated climate adjustment, predictive yield modelling, and computer-vision based detection of nutrient deficiency or pest damage from leaf imagery ^[9]. The same review identifies the absence of standardised, interpretable models, and the practical difficulty of training reliable computer-vision systems without large labelled image datasets, as recurring constraints on adoption even within the vegetable-crop domain that has received the most research attention ^[9]. For an eventual sericulture application, an equivalent image-based system would need to be trained separately on mulberry leaf rather than on the lettuce, kale, or microgreen imagery that dominates current published datasets, underlining that smart-technology adoption in this domain would require new model development rather than direct transfer from existing vegetable-crop tools.

Automated fertigation, the coordinated, sensor-triggered delivery of nutrient solution timed to crop demand rather than a fixed schedule, is among the more mature and directly transferable elements of this technology set, since the underlying control problem, maintaining target pH and electrical conductivity in a recirculating nutrient solution, does not depend on the identity of the crop being grown. Extending such systems

to a multi-tier mulberry facility would be an engineering integration task rather than a research question requiring new science, in contrast to the leaf-quality computer-vision and predictive cocoon-yield modelling applications described above, which would need dedicated development before they could function reliably in a sericulture-specific facility.

The broader implication is that digital and urban sericulture, smaller, sensor-managed indoor facilities located closer to silk processing centres rather than in traditional mulberry-growing tracts, becomes a more realistic proposition once the underlying environmental control and monitoring infrastructure is treated as a shared, transferable layer rather than something engineered separately for every individual crop. Whether such facilities are economically viable for sericulture specifically is addressed in Section 9; the technological precondition, mature, field-proven IoT and automation infrastructure, is, on the evidence reviewed here, already largely satisfied by the wider plant factory sector.

8. Sustainability and environmental perspectives

Water and land use efficiency are the most consistently documented environmental claims made for vertical farming, and both follow directly from its structural design rather than from any crop-specific property. Closed-loop hydroponic and aeroponic systems recirculate nutrient solution rather than allowing it to drain into soil, and the absence of soil evaporation and surface runoff further reduces total water demand relative to open-field irrigation; a recent quantitative review of vertical farming performance against open-field and greenhouse lettuce production confirms substantially improved water and nutrient use efficiency, while cautioning that comparable, crop-specific data for most species, mulberry included, do not yet exist ^[13]. Land use efficiency follows from the multi-tier stacking inherent to vertical farming: the same building footprint that supports one layer of field-equivalent cultivation can support several layers of indoor production, multiplying output per unit of land area, a property that becomes particularly relevant where mulberry plantations compete directly with urban expansion or other land uses for limited arable space.

Building-integrated and rooftop agriculture extends this land-use argument into already-built urban environments rather than requiring new construction. A global review of rooftop agriculture cases documents installations ranging from small-scale community gardens to commercial rooftop greenhouses, reporting building-level benefits that include improved thermal insulation and the productive use of building by-products such as greywater and waste heat as farming inputs, alongside structural load, accessibility, and regulatory constraints that limit which buildings are suitable ^[1]. No rooftop or building-integrated case study involving mulberry or silkworm rearing has yet been documented, but the underlying argument, that production can be relocated into otherwise unproductive urban space rather than displacing existing agricultural land, applies to mulberry as readily as to the vegetable crops on which the rooftop agriculture literature has so far focused.

Because controlled environment systems are physically enclosed, field-applied pesticide use can in principle be reduced or eliminated, since the structure itself excludes many of the insect pests and airborne fungal pathogens that drive conventional pesticide application; this is among the advantages most frequently claimed for vertical farming generally ^[16]. For sericulture, where pesticide residue on mulberry leaf is already a recognised hazard to the highly pesticide-sensitive silkworm, any genuine reduction in pesticide dependence would carry benefits beyond the usual environmental rationale, although,

again, this remains an extrapolation from general CEA practice rather than a documented outcome of an indoor mulberry trial.

The principal environmental qualification to all of the above is energy. Plant factory lighting and climate control are energy-intensive in absolute terms, and reviews of vertical farming sustainability consistently identify this energy demand, rather than water or land use, as the central unresolved sustainability question for the sector, recommending closer integration with renewable energy supply and high-efficiency lighting as the priority research and engineering direction ^[13]. Solar photovoltaic integration with greenhouse and vertical farm structures has been investigated for conventional horticultural crops, with reported configurations balancing the proportion of roof area allocated to panels against the light loss imposed on the crop beneath; no equivalent assessment exists for a sericulture-oriented facility, but the same trade-off, between renewable energy generation and light availability for the crop, would apply directly. Read in full, the sustainability case for controlled environment sericulture is best described as conditional rather than established: the water, land, and pesticide advantages claimed for CEA generally are plausible and, where measured for other crops, often substantial, but they are offset by an energy cost that has not yet been quantified for mulberry and silkworm production specifically, and that remains the central barrier discussed further in Sections 9 and 10.

9. Economic feasibility and commercial potential

No published economic analysis of controlled environment sericulture exists, so this section necessarily reasons from the broader vertical farming economics literature, applied with appropriate caution to a crop and product, raw silk, that differs in several relevant respects from the lettuce and leafy-green crops on which most vertical farming cost analysis has been conducted. The clearest finding from that broader literature is that energy cost, driven primarily by artificial lighting and climate control, is the dominant operating expense category and the factor most frequently cited as the cause of vertical farming business failures, even for crops with established consumer demand and proven indoor cultivation protocols ^[13].

Mulberry-for-silkworm-feed production differs from the typical vertical farming crop in a commercially important respect: the leaf itself is not sold directly to a consumer market with an established premium price, but is consumed entirely within the rearing operation as an input to cocoon and silk production. This removes the option, used by many vertical farming operators of conventional leafy greens, of recovering high capital and energy costs through a price premium on a retail product marketed as locally grown, pesticide-free, or available year-round. Any economic case for indoor mulberry would instead have to be made through the value of the silk eventually produced, meaning that the relevant comparison is not the retail price of lettuce against its production cost, but the wholesale value of raw silk against the fully loaded cost, including energy, of producing the leaf that feeds the silkworms generating that silk.

Set against this constraint, several considerations could narrow the cost gap in specific circumstances rather than across sericulture generally. High-value, specialty silk segments, where consistency of fibre quality commands a price premium over bulk commodity silk, would be better positioned to absorb a higher input cost than conventional bulk production. Facilities located to displace genuinely scarce or expensive land, such as small, intensively used plots in peri-urban sericulture tracts facing competing land pressure, would be comparing indoor production costs against an elevated, rather than typical, land

cost baseline. Renewable energy integration, discussed in Section 8, would directly address the dominant operating cost category identified above, though at the cost of additional upfront capital investment in generation infrastructure.

Scalability follows a similar logic to that observed in vertical farming generally: modular facility design, in which additional production tiers or units can be added incrementally as demand and operational confidence grow, is reported as a more financially robust growth strategy than large, single-phase capital commitments, since it allows operating cost and yield data from an initial module to inform investment in subsequent expansion ^[13]. For a prospective controlled environment sericulture venture, this would suggest beginning with a small pilot module sized to validate leaf yield, nutrient cost, and silkworm rearing outcomes before committing capital to a commercial-scale facility, an approach consistent with the research-stage status of the underlying agronomy described throughout this review.

10. Challenges and limitations

The challenges facing controlled environment sericulture divide into those inherited directly from vertical farming generally and those specific to the absence of mulberry- and sericulture-focused research. Energy intensity, already discussed in Sections 8 and 9, is the most consequential of the inherited challenges: it is identified across the vertical farming literature as the principal constraint on both environmental sustainability and commercial viability, and nothing about mulberry as a crop offers an obvious way around it, since photosynthesis and climate control demand broadly comparable energy input regardless of species ^[13].

Technical and infrastructural barriers compound the energy challenge. Multi-tier facilities require structural load capacity, climate control equipment sized to the enclosed volume, and, where aeroponic or NFT systems are used, reliable pumping and misting hardware whose failure can damage an entire production batch within hours rather than the days or weeks of tolerance that soil-buffered field cultivation provides. None of this is unique to mulberry, but it does mean that a prospective controlled environment sericulture facility would need to source or adapt equipment designed for the vegetable-crop plant factory sector, since no equipment specifically engineered for woody, repeatedly defoliated crops at production scale currently exists.

The absence of mulberry-specific indoor cultivation protocols is the more fundamental, and more directly addressable, limitation. The status review that first proposed vertical farming as a route for mulberry cultivation explicitly characterised the supporting research as being at an early stage, and the handful of subsequent studies, on Kokuso 21 aeroponic and tissue-culture propagation and on LED spectral effects on mulberry transplants, were designed as exploratory horticultural trials rather than as the basis for a defined commercial protocol ^[2, 3, 18]. Nutrient solution formulation, planting density, harvest cycle length, and pruning regime for a multi-tier mulberry system have not been established even at pilot scale, which means that any cost or yield projection for a commercial facility is, at present, necessarily speculative.

Economic constraints and knowledge gaps reinforce one another. Investment in mulberry-specific CEA research requires some prior expectation of commercial viability, while a defensible viability assessment requires the agronomic and yield data that only dedicated research can supply. Breaking this circularity is likely to depend on publicly funded or institutionally supported pilot research, of the kind sericulture research institutes are well placed to conduct, rather than on

private investment alone, since the commercial case cannot currently be made with confidence in either direction. This is, in itself, a fair summary of the current state of the literature: not that controlled environment sericulture has been shown to fail, but that it has barely been tested, and the research gaps identified throughout this review, set out more fully in Section 11, are the direct consequence of that early stage.

11. Research gaps and future perspectives

The gaps identified across the preceding sections, summarised in Table 3, point toward a coherent near-term research agenda rather than an unstructured list of unknowns. At the agronomic core, mulberry-specific nutrient solution formulation stands out as the most immediately tractable priority: existing soilless mulberry trials have used generic horticultural nutrient mixes rather than formulations designed around the leaf protein and bioactive compound profile that matters specifically for silkworm nutrition^[3, 18], and correcting this is primarily a matter of conducting the relevant trials rather than developing fundamentally new technology.

Plant breeding presents a longer-horizon but potentially higher-value opportunity. No mulberry cultivar has been bred or selected specifically for short-internode, high leaf-to-stem ratio growth suited to dense, multi-tier indoor planting, in contrast to the dwarf and compact cultivars that breeding programmes have already produced for crops such as lettuce and tomato grown in vertical systems. Given mulberry's existing genetic diversity and the precedent set by selection for other desirable traits in conventional sericulture breeding, developing or screening for a compact growth habit appears a realistic, if multi-year, research direction rather than a speculative one.

Artificial intelligence assisted sericulture, extending the predictive modelling and computer-vision approaches already developed for vegetable plant factories^[9] to mulberry leaf quality grading and, eventually, to direct monitoring of silkworm rearing conditions, represents a further opportunity that depends on the prior availability of labelled mulberry-specific image and sensor datasets rather than on any new underlying algorithmic development. Renewable-energy-integrated facility design, whether through dedicated solar photovoltaic capacity or building-integrated agrivoltaic structures, addresses the energy constraint identified throughout this review directly, and should be treated as a design requirement for any pilot facility rather than as a later retrofit.

Rooftop and urban sericulture, building on the established rooftop agriculture literature for vegetable crops^[1], offers a route to test controlled environment mulberry cultivation in proximity to existing silk processing infrastructure rather than in isolation from it, which would also allow early pilot facilities to draw on existing urban building stock rather than requiring purpose-built premises. Precision environmental control, the coordinated management of temperature, humidity, carbon dioxide, and light spectrum specifically calibrated to mulberry rather than adapted from generic leafy-crop settings, ties together each of the preceding priorities and is, ultimately, the technical objective that a successful controlled environment sericulture system would need to achieve. None of these directions requires a conceptual breakthrough; each requires dedicated, well-designed research of a kind that has, to date, simply not yet been carried out for this particular crop and production system.

Table 3: Identified research gaps and proposed future research priorities for controlled environment sericulture

Research gap	Current status	Proposed future direction
Mulberry-specific nutrient solution formulation	Soilless mulberry trials to date use generic horticultural nutrient mixes rather than formulations targeted at silkworm-relevant leaf composition ^[3, 18]	Develop and trial macro- and micronutrient ratios optimised for leaf protein and bioactive compound content rather than vegetative biomass alone
Compact or dwarf mulberry genotypes for multi-tier systems	No mulberry cultivar has been bred or screened specifically for short-internode growth suited to stacked indoor production	Screen existing germplasm collections for compact habit and high leaf-to-stem ratio; consider targeted breeding informed by precedent in other vertically farmed crops
Integrated facility design linking cultivation and rearing	Mulberry soilless production and silkworm rearing-house management are documented as separate bodies of literature, with no published integrated facility study ^[2, 3, 14]	Pilot-scale facilities combining shared climate control for both the crop chamber and the rearing chamber, with rearing trials comparing indoor- and field-grown leaf
Renewable-energy-matched operation	Energy intensity is recognised as the principal constraint on vertical farming viability generally ^[13] , but has not been assessed for a sericulture-specific facility	Lifecycle and techno-economic assessment of solar photovoltaic or agrivoltaic-supported controlled environment sericulture
Urban and rooftop sericulture	Rooftop and building-integrated agriculture is established for vegetable and ornamental crops ^[1] , with no documented mulberry or silkworm application	Feasibility assessment of rooftop or building-integrated mulberry-silkworm modules located near urban silk processing clusters
AI-assisted environment and rearing management	Computer-vision and predictive modelling tools are reviewed for vegetable plant factories ^[9] , with no mulberry-specific datasets or models reported	Development of mulberry leaf-quality grading and larval-health monitoring models, trained on dedicated sericulture imagery and sensor data

12. Conclusion

Controlled environment sericulture, as examined throughout this review, is best understood as a coherent and technically plausible research direction rather than as a demonstrated production system. Mulberry's rapid growth, propagation flexibility, and documented, if limited, responsiveness to soilless cultivation and LED spectral management indicate that the crop is not an obviously poor fit for indoor, multi-tier production. The wider plant factory and vertical farming sectors have already solved much of the underlying environmental control and monitoring engineering that a mulberry facility would need, which lowers the technical barrier to entry relative to building

such a system from first principles. What remains absent is the sericulture-specific evidence base: defined nutrient and lighting protocols for mulberry grown as silkworm feed rather than for direct sale; rearing trials comparing indoor- and field-grown leaf under matched conditions; and a credible economic assessment that accounts for the absence of a retail price premium available to most vertical farming crops. Until that evidence exists, claims about year-round rearing, disease reduction, or improved cocoon quality under controlled environment sericulture should be treated as reasoned hypotheses grounded in established sericulture physiology and CEA performance elsewhere, not as established findings.

The research priorities set out in Section 11, mulberry-specific nutrient formulation, compact cultivar development, AI-assisted monitoring extended to this crop, renewable-energy-matched facility design, and rooftop or urban pilot deployment, define a realistic path from the current, fragmentary evidence base toward a properly tested system. Sericulture institutions already possess the entomological and mulberry agronomy expertise that such a programme would require; what has been missing is the deliberate combination of that expertise with controlled environment engineering. Supplying that combination, through dedicated pilot-scale research rather than further extrapolation from adjacent crops, is the clearest next step toward establishing whether controlled environment sericulture can become a genuine contribution to climate-resilient, sustainable silk production.

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