E-ISSN: 2618-0618
P-ISSN: 2618-060X

NAAS Rating (2025): 5.20
www.agronomyjournals.com
2025; SP-8(10): 15-21
Received: 06-07-2025
Accepted: 08-08-2025

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Sustainable sericulture through solar energy integration

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DOI: https://www.doi.org/10.33545/2618060X.2025.v8.i10Sa.3945

Abstract
Sericulture, the cultivation of silkworms and associated mulberry leaf production, is highly sensitive to water scarcity, energy access and environmental control due to conventional irrigation and reeling practices. The integration of solar energy technologies into sericulture presents a transformative approach to enhancing sustainability, productivity and economic viability in silk farming. Solar-based technologies offer decentralized and cost-effective solutions to many of the challenges faced by sericulturists, especially in off-grid or low-resource settings. This review focuses on recent innovations in solar drip irrigation for mulberry, solar-powered spinning and reeling machines (e.g. Unnati, Silky Spin, Resham Sutra's machines), solar/hybrid cold storage units, solar dryers for cocoons, solar-powered leaf cutting machines, IoT-driven environmental monitoring, solar water heating systems for degumming and reeling, and solar tunnel dryers for silkworm pupae. By reducing dependence on conventional energy sources and mitigating environmental impact, solar innovations contribute to cost-effective and eco-friendly sericulture practices. The research highlights successful case studies from rural India, demonstrating improved yield quality, reduced operational costs and increased resilience against climate variability. The findings advocate for broader adoption of solar solutions in sericulture, positioning renewable energy as a catalyst for rural development and green entrepreneurship.

Keywords: Solar, sustainability, innovation, cocoons, machines, energy

Introduction

Sericulture is an agro-enterprise that combines mulberry cultivation with silkworms rearing, cocoon processing and textile production. Sericulture, the cultivation of silkworms for silk production, is crucial in many rural economies but faces issues with labor intensity, climate variability and limited access to clean energy.

Silk is considered superior to other fibers because of its unique qualities such as high-water absorption, resistance to heat, excellent dyeing capability, and natural luster. The body temperature and moisture levels of insects are influenced by multiple factors, yet insects exhibit remarkable adaptability, maintaining stable internal temperature and hydration even under extreme environmental conditions (Rahmathulla, 2012) [18].

Key inputs include mulberry leaves, suitable temperature, humidity, water and energy for processes like degumming, reeling, drying and spinning. Unlike mulberry cocoons, tasar cocoons are more challenging to soften because of their calcium oxalate and tannin content, which requires the use of alkaline agents like sodium carbonate or bicarbonate for proper degumming (Jolly *et al*., 1979; Sonwalkar, 1993) [8, 20]. Traditional cooking methods typically depend on firewood, rice husk or coal, leading to higher processing costs as well as environmental impacts such as deforestation and greenhouse gas emissions.

However, conventional practices rely heavily on firewood for heating, manual thigh-reeling methods that are labor-intensive and harmful to artisans and sun-drying processes that are slow and weather-dependent. These methods raise sustainability concerns-deforestation, high drudgery, inefficiency, and health risks among workers. Traditional methods rely heavily on grid electricity or biomass/wood for heating, hand labour and conventional irrigation, which often are inefficient, costly and environmentally unsustainable.

Solar energy, due to its decentralised nature and availability in many sericulture-growing regions, holds promise.

The integration of solar-based technologies offers a sustainable pathway to enhance productivity, energy efficiency, and resilience against climatic challenges. The system performs almost uses solar power, making it suitable in off-grid or erratic electricity regions. Water savings and increased yield make this promising for small and marginal farmers. Solar-powered technologies have emerged as promising interventions, offering eco-friendly, cost-effective and scalable solutions (Burney *et al*., 2010 [4]; Grant *et al*., 2022) [2, 4].

Materials & Methods

1. Solar Drip Irrigation Kit (SDIK) for Mulberry Leaf Production

Rajendran *et al*. (2025) developed a Solar Drip Irrigation Kit (SDIK) integrating a solar-powered nano pump, overhead storage and inline drip laterals for supplemental irrigation in rainfed mulberry fields.

The study compared three irrigation methods—Solar Drip Irrigation Kit (SDIK), Conventional Drip Irrigation (CDI), and Surface Irrigation (SI). Figure 1(a) and 1(b) shows the installation of solar drip irrigation kit in mulberry garden with 1000 L drum elevated 5 ft, PVC pipes to field, inline drip lateral (12 mm OD; 2.4 L/hr emitters), spacing 90 cm between laterals. Solar nano pump (0.25 HP) powered by an 80 Wp solar PV panel lifts water. Conventional drip irrigation (CDI) and surface irrigation (SI) used as control as shown in Figure 1(a) and 1(b).

It found that mulberry growth and yield under SDIK matched those achieved with CDI. Compared to SI, SDIK boosted leaf yield by 37%, reduced water usage by 24%, and increased water productivity by 44%. These findings highlight SDIK as a promising and cost-effective irrigation solution for small rainfed sericulture farmers aiming to sustainably enhance mulberry production. The costs initial solar panel, pump, drip lines likely higher than SI, but life cycle savings in water and energy may offset. Full cost-benefit beyond the study is less reported.

Similar studies confirm that drip irrigation can enhance yield by 20–40% (Pande *et al*., 2003) [17], improve water productivity (Yang *et al*., 2023) [26], and increase farm income (Bawa *et al*., 2023) [1].

Fig 1 (a): Solar drip irrigation kit with two solar photovoltaic panels (80 Wp)

Fig 1(b): Solar drip irrigation kit installed in mulberry garden

2. Solar-Powered Leaf-Cutting Machines

Liu *et al*., (2025) [17] designed the machine to minimize damage during stubble cutting, since improper cutting can cause root decay, hinder plant rejuvenation or even lead to the death of mulberry trees.

Its prototype consists of a flat, suspended circular saw-type cutter, a star-wheel feeding and separation unit, a lifting mechanism for the cutting platform, a signal acquisition setup equipped with torque sensors and a chassis/frame operated through the tractor's power take-off and hydraulic system. The optimal parameters determined were disc saw line speed of 74 m/s, star-wheel height of 727 mm above the ground and a cutting speed ratio of 93.

Under these conditions, the cutting energy consumption was approximately 241 mJ per meter of cut, with a stubble quality score of about 8.5 on the evaluation scale. Validation trials recorded an average energy consumption of around 246 ± 7 mJ and a stubble score of 8.3 ± 0.87.

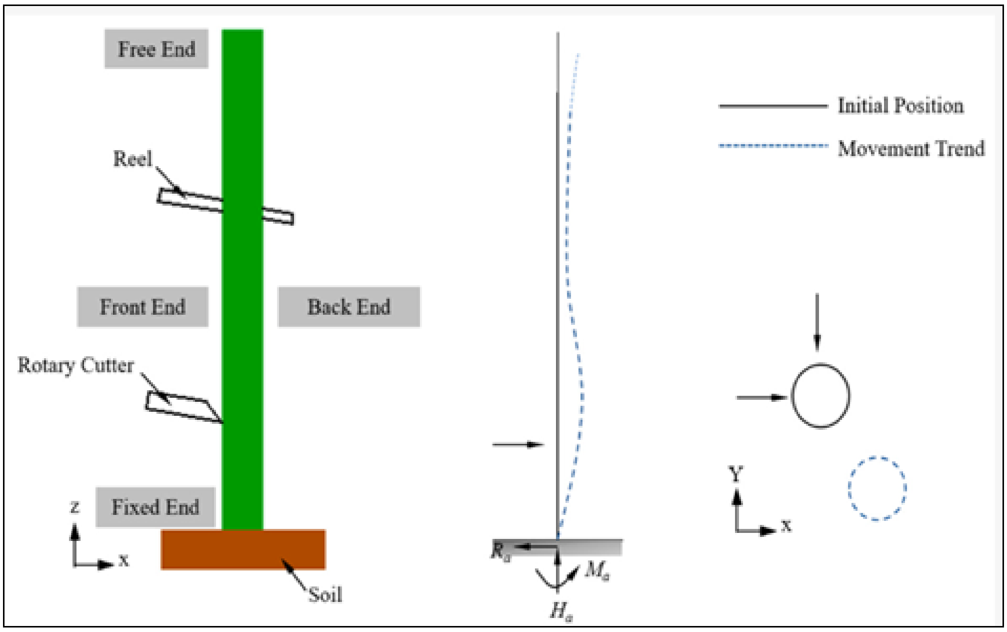

Fig 2: Schematic diagram of displacement analysis for mulberry branches [14]

The image in figure 2 illustrates the cutting and deformation process of a mulberry stalk during stubble cutting. On the left, the diagram shows a vertical mulberry stalk fixed in the soil at its base (fixed end) with a free end at the top. A reel and rotary cutter apply force from the front and back ends, respectively. The stalk is anchored in the soil at the bottom, representing resistance against motion.

The middle section demonstrates the bending effect, with the stalk's initial upright position shown as a solid line and its movement trend (due to applied cutting force) indicated by the dashed line. The applied moment Mg and horizontal force Hg act at the base, showing bending stresses around the fixed point in the soil.

On the right side, a top-view schematic depicts the force direction and lateral displacement, showing how the stalk deflects from its initial circular cross-section position (solid line) to a displaced position (dotted circle) along the X–Y axis.

With these optimized parameters, the machine was found to meet the required quality standards for mulberry harvesting and stump cutting, while also providing valuable insights for advancing mechanization in this area. The study highlights that disc saw line speed plays the most critical role in determining stubble quality, whereas energy consumption is mainly affected by cutting speed ratio, followed by star-wheel height, and then disc saw line speed.

Verma *et al*., (2018) [25] compares improved machines for cutting preparation, shoot harvesting with traditional methods to show reduction in labor, energy, cost. Sun *et al*., (2012) [21] analysed blade shape via simulation (ANSYS/LS-DYNA) to optimize cutter parts. Tumusiime (2016) [23] developed manual leaf chopper design, capacity, efficiency which is good for understanding simpler machines.

3. Solar power operated cooking device for cocoon

Since the 1990s, solar energy has been applied in cocoon processing for purposes such as water heating, solar drying, and operating reeling machines (Inbanathan, 2003; Singh, 2011) [6, 19]. However, tasar reeling centers, typically situated in remote rural areas, often suffer from inconsistent grid electricity supply, underscoring the need for decentralized solar-based solutions (Gupta, 1989; Kathari *et al*., 2010) [5, 9].

Khan *et al*. (2023) [11] developed a solar-powered cocoon cooking system that utilizes PV-generated electricity and preheated water from a solar geyser as alternatives to conventional fuels. This approach highlights the potential of renewable energy solutions to address specialized needs in sericulture.

The cooking system developed by Khan *et al*. (2023) [11] consists of three integrated components: a 10-kW solar PV plant installed by Solace Renewable Energy Pvt. Ltd. to power a 4.5 kW coil heater, a solar geyser that preheats water to 40–50 °C to lower energy demand for boiling, and a stainless-steel cooking chamber designed with two sections—one for boiling and another for pressurized steaming. The chamber can process around 1,500 cocoons per batch using about 50 liters of water. The system operates either on solar-generated electricity or switches to grid power as backup. The cocoon cooking process involves treating with sodium carbonate and bicarbonate (5 g/L each), followed by 20 minutes of boiling and 30 minutes of steaming under pressure as shown in figure 3. Performances and economic outcomes of solar power operated cooking device for tasar cocoons as shown in Table 1.

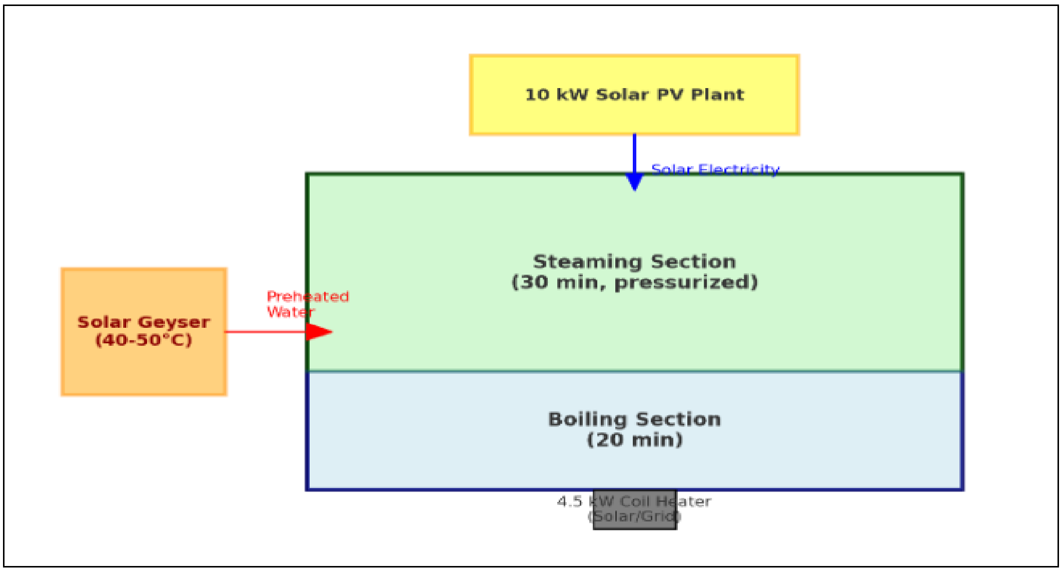

Fig 3: Schematic of solar power operated cooking device for Tasar cocoons [11]

Table 1: Performances and economic outcomes of solar power operated cooking device for tasar cocoons

Parameters	Results
Cooking efficiency	~95%, equivalent to conventional open-bath and peroxide-based methods
Cocoon quality & reeling performance	No significant variation in filament length, denier, NBFL, reelability, or silk recovery compared with traditional processes
Cost of cooking (per 1000 cocoons)	₹50–58 with solar (depending on availability); comparable with grid (₹57); lower than firewood (₹70)
Energy savings	12–55% reduction in energy consumption due to solar geyser water preheating
Overall outcome	Technical performance matches conventional methods while offering economic savings and reduced environmental burden compared to firewood

4. IoT-Driven Environmental Monitoring

Sericulture, the practice of raising silkworms for silk production, is a long-established activity that demands precise environmental control. Conventional methods depend largely on manual supervision of conditions like temperature, humidity, and light.

The study by Jegadeesan *et al.* (2021) [7] presents an IoT-enabled Smart Incubator system that automates the silkworm rearing process through the use of ATMEGA 328P microcontrollers, sensors and mobile application support. This review examines the system in detail, evaluating its hardware and software elements as well as its significance in advancing the modernization of sericulture.

The proposed IoT-based incubator system integrates temperature, humidity and light sensors with ATMEGA 328P microcontrollers and NodeMCU Wi-Fi modules, enabling real-time data transmission to farmers through a mobile application. It's hardware setup features a 16x2 LCD display, environmental sensors and actuators such as fans and bulbs, while the software framework is developed using Arduino IDE. The system autonomously manages conditions—for example, activating fans when temperatures exceed set limits or switching on lights under low illumination. Findings from the study indicate efficient environmental control and a significant reduction in manual monitoring.

This IoT-based approach effectively addresses the challenges associated with labor-intensive monitoring and the susceptibility to errors inherent in manual control systems. Furthermore, the system provides real-time alerts, enabling farmers to make informed decisions remotely. Crucially, it facilitates healthier development of larvae, reduces cocoon mortality rates and improves the overall quality of cocoons.

The evaluated system aligns with the wider movement toward smart agriculture, where IoT and automation are transforming conventional farming practices. Comparable technologies include wireless sensor networks applied in precision farming (Le & Tan, 2015) and IoT-driven smart farming approaches (Sushanth & Sujatha, 2018) [22]. Within sericulture, these advancements hold the potential to narrow the gap between India and China in terms of silk production and quality.

5. Solar Water Heating Systems for Degumming and Reeling

Kathari *et al.* (2010) [9] introduced a solar water heating system integrated with a mini-boiler and heat recovery unit for multi-end reeling units. Solar thermal systems are well suited for degumming and water heating because temperatures are moderate (50-80 °C). In the conventional process, 113.48 kg of firewood is burnt for cooking and reeling activity for the production of 10 kg raw silk in 10 basin multi-end reeling unit and for similar production under new energy efficient management layout plan it reduces to 25 kg, resulting a saving of 77.97% in firewood consumption.

The result suggested energy efficiency is improved utilization of solar thermal energy for cocoon cooking and reeling water heating which show in Table 2. Hereby the environmental benefits show the significant reduction in CO_2 and other emissions, mitigating ecological imbalance as depicted in Table 3. The economic viability gives the payback period of 2.3 years due to firewood savings.

Table 2: Energy consumption in conventional process

Activity	Energy consumption, kcal	Firewood consumption, kg
Cocoon cooking	1,23,840	89.35
Hot water for reeling basin	33,440	24.13
Total	1,57,280	113.48

Table 3: Energy and firewood consumption in new energy efficient process with solar water heating system

Activity	Energy consumption, kcal	Firewood consumption, kg
SWHS (1000 LPD) at 80% efficiency	44,000	-
50 kg mini-boiler	34,650	25
HRU energy recovery	25,200	-
The combined reduction of energy loss by mini-boiler, insulated bench and additional hot water tank	53,430	-
Total	1,57,280 25	25

Conventional reeling requires 20 kg firewood per kg of raw silk, consuming ~145,000 MT of firewood annually in India (Dhingra et., 2004) [3]. Solar-assisted systems thus present a transformative alternative as cost savings, reduced deforestation, less smoke / health impact.

6. Solar Tunnel Dryers for Silkworm Pupae

Manvi and Shriramulu (2022) [16] designed a mobile forced-convection solar tunnel dryer with a batch capacity of 60 kg and dimensions of approximately 6.58 × 1.8 × 1.1 m (L×W×H). The system consisted of a solar collector, a tunnel-type drying chamber and a fan-assisted exhaust unit that maintained positive airflow across the drying material as shown in figure 1.

Experiments conducted with fresh silkworm pupae showed notably shorter drying durations compared to open-sun methods while achieving the desired final moisture levels within acceptable processing periods, without compromising product quality. The researchers documented key operating parameters such as dryer temperature and airflow and analyzed performance indicators including drying rate, thermal efficiency and outlet air temperature. Its mobile design makes the unit well-suited for decentralized, village-scale applications requiring relocation or operational flexibility.

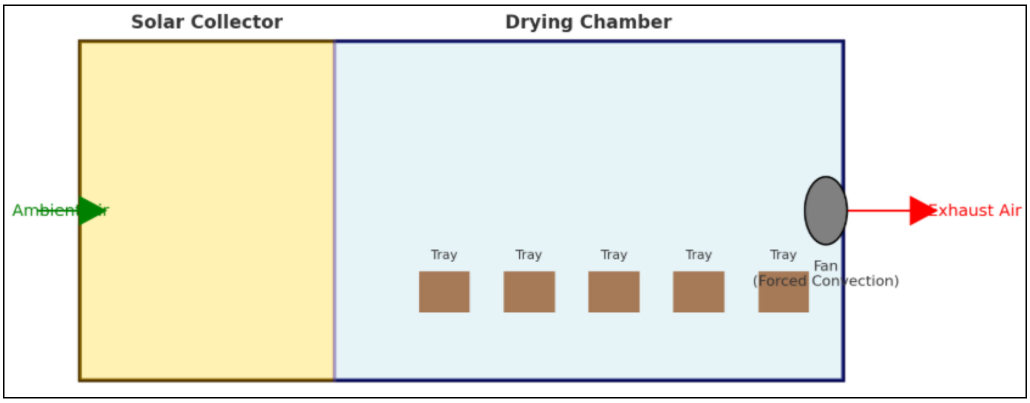

Fig 4: Schematic of forced convention mobile solar tunnel dryer [16]

The study reported that the developed dryer had a batch capacity of about 60 kg and was constructed with an MS frame covered by polyethylene or glass, as specified in the design. By employing forced convection, the system significantly reduced drying time while enabling drying at elevated yet controlled temperatures that successfully met the required quality standards.

Previous research on thin-layer and tunnel dryers (Usub *et al.*, 2010 [24], Singh 2011 [19], Kittibunchakulet *et al.*, 2025) [12] has examined drying kinetics and modeled thin-layer drying behavior for silkworm pupae. These studies consistently demonstrate that tunnel dryers achieve shorter drying times than open-sun drying, with drying performance being highly influenced by factors such as airflow rate, inlet temperature, and initial moisture content. Optimized forced-convection tunnel dryers typically reduce drying duration by 30–50% compared to natural convection systems.

Results

- **Water Use Efficiency:** Solar drip irrigation kits (SDIK) improve water productivity by 44% compared to surface irrigation in mulberry cultivation. This shows a clear benefit for drought-prone or rain-fed sericulture.
- **Energy Savings:** Solar thermal heating for degumming and solar dryers for cocoons can drastically cut energy requirements – reducing reliance on electricity or biomass.
- **Yield / Quality:** Leaves from SDIK show higher yield; cocoon drying methods maintain silk yield and strength comparable to conventional methods.
- **Capital and Maintenance Costs:** Although operational savings are good, initial costs for solar PV, thermal collectors, dryer structures etc. can be high for small farmers. Subsidies or financing mechanisms are key.
- **Weather Dependence:** Solar drying, solar water heating, solar PV are all dependent on sunshine. Cloud cover, rainy seasons can reduce efficiency as backup systems needed.

Discussions

1. **Quality Control:** Uniformity in drying, avoiding UV or over-heating damage, ensuring moisture control is essential for preserving silk quality. More studies needed quantifying fine fibre quality under solar process conditions.
2. **Integration and Scaling Up:** Many studies are pilot scale. Scaling up requires reliable supply chains for parts (solar panels, sensors, etc.), skilled persons for maintenance, and consistent adoption among farmers.
3. **Specific Technologies Under-studied:** Leaf cutting machines (solar powered) and solar tunnel dryers for pupae are underrepresented in published literature. More field trials needed.

4. **Power Supply for IoT and Automation:** Sensors, actuators need reliable power; pairing these with solar + batteries are promising but not always implemented. Data connectivity (remote/rural areas) can be spotty.
5. **Economic Analyses:** Full life-cycle cost analyses including payback period, maintenance, replacement are fewer. Economic impacts beyond yield (e.g. improvements in health, labour savings) need quantification.

Conclusion
Solar-based technologies offer significant opportunities to make sericulture more sustainable, efficient and adaptable. By incorporating innovations such as solar-powered pumps, drip irrigation systems and dryers, farmers can reduce their reliance on conventional energy sources while optimizing water use, labor efficiency and climate regulation. Research indicates that solar-driven drip irrigation improves leaf yields, enhances water productivity and conserves water in rainfed mulberry fields.

The integration of solar energy with modern tools like IoT, AI, and real-time monitoring systems further strengthens the sector by helping predict pest infestations, control diseases, and maintain favorable rearing conditions. This leads to reduced losses as well as better quality of cocoons and silk.

Despite these advantages, challenges persist. High initial investment in solar equipment, technological maintenance in remote or resource-constrained regions, limited farmer awareness, and inadequate after-sales support remain barriers to adoption. Addressing these through subsidies, policy support, training and efficient extension services could accelerate wider acceptance.

Ultimately, integrating solar innovations into sericulture supports long-term sustainability, strengthens rural livelihoods, and enhances climate resilience. With the right policies, investments and farmer engagement, solar-powered systems can help sericulture thrive under changing environmental conditions by boosting productivity, lowering environmental footprints and increasing farmer incomes.

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