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The Green Transformation of "China's Silk Capital": A Multi-Dimensional Case Analysis of Low-Carbon Upgrading across Nanchong's Silk Industry Chain

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Abstract

Traditional industries face distinctive challenges in achieving low-carbon transformation, yet their upgrading pathways remain underexplored compared with those of high-tech and heavy-emitting sectors. This paper addresses this gap by examining the silk industry of Nanchong, a prefecture-level city in Sichuan Province officially designated as "China's Silk Capital" (2005) and the "Origin of Silk" (2016). Nanchong possesses the most complete cocoon-silk-textile industry chain in southwestern China, spanning sericulture, reeling, weaving, dyeing, garment manufacturing, and cultural-tourism integration. Drawing on embedded multi-case study methodology (Yin, 2018) and an industry-chain life cycle analytical framework, we select representative enterprises at each major segment of the value chain — Bubisi Organic Agriculture (upstream sericulture), Yiger Textile and Shuncheng Textile (midstream reeling and weaving), Jiafeng Fashion (downstream garment manufacturing), and the Litai Fung Group's eco-standard industrial park in Yilong County — and analyze their low-carbon upgrading strategies across five dimensions: organic raw material substitution, intelligent equipment-based energy conservation, clean production in dyeing and finishing, comprehensive utilization of sericulture by-products (mulberry tea, mulberry fruit, silk protein extraction), and silk cultural-tourism fusion. Our analysis reveals that the silk industry chain possesses an inherent "green endowment" — silk is a natural protein fiber derived from a renewable biological cycle — but that this endowment is unevenly realized across chain segments. Upstream sericulture can function as a net carbon sink when managed organically, while midstream dyeing and finishing remain the principal emission hotspots. We identify a "green sandwich" pattern in which the industry's upstream and downstream segments are relatively amenable to low-carbon upgrading, while the midstream processing segment faces the greatest technical and financial barriers. We propose an integrated upgrading model — the "Silk Green Chain" framework — that combines organic certification, digital lean manufacturing, circular by-product valorization, and cultural branding to achieve simultaneous decarbonization and value-added enhancement. The findings carry implications for traditional industry clusters in developing regions seeking to reconcile heritage preservation with carbon neutrality imperatives.

Keywords

Silk industry; low-carbon upgrading; traditional industry transformation; Nanchong; embedded multi-case study; industry chain life cycle; green manufacturing; China's Silk Capital.

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1. Introduction

1.1. Research Background

The global textile and apparel industry is responsible for an estimated 8–10% of worldwide greenhouse gas emissions, exceeding the combined emissions of international aviation and maritime shipping. Within this sector, natural fiber production — including silk — is often perceived as inherently "green" compared with synthetic alternatives[1]. However, this perception obscures significant variation in carbon intensity across different stages of the textile value chain. Dyeing and finishing alone account for approximately 36% of the textile industry's total carbon footprint, while energy-intensive reeling, weaving, and garment manufacturing processes contribute additional emissions that are highly sensitive to equipment vintage, energy source, and management practices[2].

China dominates global silk production, accounting for approximately 80% of world raw silk output. Within China, Sichuan Province is the largest silk-producing province, and Nanchong is its preeminent silk city. In 2005, the China Silk Association conferred upon Nanchong the title of "China's Silk Capital" (中国绸都), and in 2016, the city was further designated as the "Origin of Silk" (丝绸源点), recognizing its archaeological and historical significance in the development of sericulture. Nanchong possesses a complete industrial chain encompassing mulberry cultivation, silkworm rearing, cocoon production, silk reeling[3], fabric weaving, printing and dyeing, knitting, and garment manufacturing — the most comprehensive and scaled cocoon-silk-textile production system in southwestern China. The Nanchong Municipal Government's 14th Five-Year Plan for the Silk, Textile, and Garment Industry (hereafter "the 14th FYP for Silk") sets the strategic goal of building Nanchong into a "national silk, textile, and garment center city."[4]

Yet the silk industry, like all traditional manufacturing sectors, confronts mounting pressure from China's dual-carbon strategy. The national Action Plan for Carbon Dioxide Peaking Before 2030 calls for thoroughly implementing the green manufacturing project, vigorously promoting green design, and building green factories and industrial parks. For a city whose cultural identity and economic base are deeply intertwined with silk, the question of how to achieve low-carbon transformation without sacrificing the industry's heritage value and employment function is both economically consequential and culturally sensitive.

1.2. Research Gap

The existing literature on low-carbon industrial transformation is dominated by studies of heavy-emitting sectors — steel, cement, petrochemicals, and power generation — and of high-technology sectors — semiconductors, electric vehicles, and renewable energy[5]. Traditional light-manufacturing industries such as silk, tea, ceramics, and handicrafts have received comparatively little scholarly attention in the low-carbon transition literature, despite their economic importance to hundreds of cities in China's central and western regions. When textile industry decarbonization is studied, the focus tends to be on synthetic fibers (polyester, nylon) and fast fashion, with natural silk treated as a niche product unworthy of systematic analysis.

This neglect is problematic for three reasons. First, traditional industries employ millions of workers in less-developed regions where alternative employment is scarce, making abrupt decarbonization socially costly. Second, traditional industries often possess latent "green endowments" — biological raw materials[2], artisanal production techniques, cultural heritage value — that can be leveraged for low-carbon upgrading in ways fundamentally different from heavy industry. Third, the industry-chain perspective is essential for understanding traditional industry decarbonization, because carbon intensity varies dramatically across chain segments, and upgrading interventions at one segment may create co-benefits or trade-offs at others.

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1.3. Research Questions and Contribution

This paper addresses three research questions. First, what are the carbon emission characteristics and hotspots across the silk industry chain in Nanchong? Second, what low-carbon upgrading strategies are being pursued by representative enterprises at each chain segment, and what factors enable or constrain their implementation? Third, can a coherent framework be constructed for the green transformation of a complete traditional industry chain that simultaneously achieves carbon reduction, value enhancement, and heritage preservation?

The paper makes three contributions. First, it provides the first systematic English-language analysis of low-carbon upgrading across a complete silk industry chain, using Nanchong as an empirically rich case. Second, it develops the "Silk Green Chain" framework as an integrated model for traditional industry decarbonization that may be transferable to other heritage-based manufacturing clusters. Third, it extends the embedded multi-case study methodology by combining it with an industry-chain life cycle analytical lens, demonstrating how case selection along a value chain can illuminate systemic transformation dynamics that single-enterprise or single-segment studies miss.

2. Literature Review

2.1. Low-Carbon Transformation of Traditional Industries

The low-carbon transformation of traditional industries has been framed through several theoretical lenses. Ecological modernization theory (Mol & Spaargaren, 2000) posits that economic growth and environmental protection can be reconciled through technological innovation and institutional reform, without requiring deindustrialization[6]. This perspective is particularly relevant to traditional industries, where the goal is upgrading rather than phase-out. The concept of "green upgrading" in global value chains (Humphrey & Schmitz, 2002; De Marchi et al., 2019) extends this logic by examining how environmental standards and practices are diffused through buyer-supplier relationships, certification systems, and industrial policy.

In the Chinese context, the "green manufacturing system" (绿色制造体系) established by the Ministry of Industry and Information Technology provides the institutional architecture for traditional industry upgrading, including the designation of green factories, green industrial parks, green supply chains, and green products. The national policy framework explicitly calls for the creation of green factories, green industrial parks, and green supply chains, with the transformation of traditional manufacturing as a key implementation priority.[5] However, empirical studies of how specific traditional industries navigate this system remain scarce

2.2. The Silk Industry's Environmental Profile

Silk production involves a distinctive biological-industrial hybrid value chain. The upstream segment — mulberry cultivation and silkworm rearing — is fundamentally agricultural, with carbon dynamics governed by photosynthesis, land use, and organic waste management. Mulberry trees (Morus spp.) are perennial woody plants with significant carbon sequestration capacity; studies have estimated that well-managed mulberry plantations can sequester 5–15 tonnes of CO_2 per hectare per year, depending on planting density, management practices, and climate. Silkworm rearing produces organic waste (silkworm excrement, or "sha," and spent mulberry branches) that can be composted or converted into biogas, potentially closing the nutrient loop[7].

The midstream segment — cocoon drying, silk reeling, degumming, weaving, and especially dyeing and finishing — is the most energy- and water-intensive portion of the chain. Cocoon drying and reeling require sustained heat input; degumming involves boiling cocoons in alkaline solutions; and conventional dyeing and finishing consume large quantities of water,

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chemical dyes, and thermal energy while generating polluted effluent. Studies of the Chinese textile industry indicate that dyeing and finishing can account for 40–60% of total water consumption and 30–40% of total energy consumption across the textile value chain[4].

The downstream segment — garment design, cutting, sewing, and packaging — is comparatively less carbon-intensive per unit of value added, but faces pressures related to material waste (cutting losses), logistics emissions, and fast-fashion consumption patterns.[5]

2.3. Industry Cluster Upgrading Theory

Nanchong's silk industry is organized as a geographically concentrated industrial cluster, which the literature identifies as having both advantages and disadvantages for green transformation. Porter's (1998) cluster theory suggests that geographic concentration facilitates knowledge spillovers, specialized supplier development, and collective action for shared infrastructure — all of which can accelerate green upgrading. However, cluster lock-in effects (Grabher, 1993) can also retard transformation when established firms resist change and shared norms perpetuate traditional practices[8].

The evolutionary economic geography literature (Boschma & Frenken, 2011) emphasizes the role of "related variety" — the presence of technologically related but distinct industries — in enabling regional diversification and renewal. For Nanchong's silk cluster, related variety exists in the form of silk by-product industries (mulberry tea, mulberry fruit processing, silk protein cosmetics), cultural tourism, and bio-textile innovation, all of which represent potential diversification pathways that simultaneously reduce the cluster's carbon intensity and increase its economic resilience.

3. Analytical Framework and Methodology

3.1. Industry-Chain Life Cycle Analytical Framework

We adopt an industry-chain life cycle perspective that traces carbon-relevant activities across three major segments of the silk value chain: upstream (sericulture), midstream (processing), and downstream (manufacturing and branding). Within each segment, we analyze five dimensions of low-carbon upgrading: (1) organic raw material substitution, (2) intelligent equipment-based energy conservation, (3) clean production in dyeing and finishing, (4) comprehensive utilization of sericulture by-products, and (5) cultural-tourism integration and value-chain repositioning. These five dimensions were identified through an initial screening of Nanchong's silk industry policy documents and cross-referenced with the academic literature on textile industry decarbonization[5].

The life cycle perspective is critical because interventions at one segment affect others. For instance, organic sericulture (upstream) produces cocoons of different quality characteristics that influence reeling efficiency (midstream)[7]; clean dyeing technologies (midstream) enable eco-certification that enhances brand value (downstream); and by-product valorization (cross-cutting) creates additional revenue streams that can cross-subsidize green investments in the processing segment.

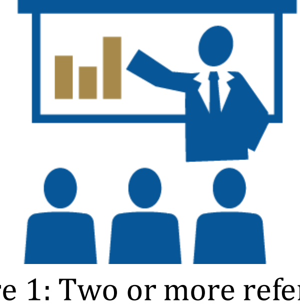

Figure 1: Two or more references

3.2. Embedded Multi-Case Study Design

Following Yin (2018), we employ an embedded multiple-case study design in which the overall case is Nanchong's silk industry chain, and the embedded units of analysis are individual enterprises representing different chain segments. This design allows us to analyze both within-case (enterprise-level) dynamics and cross-case (chain-level) patterns[8].

Case selection. Enterprises were selected using a purposive sampling strategy based on three criteria: (a) they represent different segments of the silk value chain; (b) they have implemented observable low-carbon or green upgrading initiatives; and (c) sufficient publicly available information exists for analysis. The selected cases are presented in Table 1.

Table 1: Selected cases across the silk industry chain

Chain Segment	Enterprise	Key Characteristics	Low-Carbon Relevance
Upstream: Organic sericulture	Bubisi (布碧丝) Organic Agriculture	Organic mulberry cultivation and silkworm rearing	Organic raw material substitution; carbon sink potential
Upstream-Midstream: Integrated eco-park	Litai Fung Group (利达丰集团, Hong Kong) / Yilong Industrial Park	Eco-standard garment park exceeding EU environmental standards; 16,000 mu (approx. 1,067 hectares) organic sericulture base in Yilong County	Full-chain integration; international eco-certification
Midstream: Reeling and weaving	Yiger Textile (依格尔纺织)	Large-scale silk reeling and fabric production; provincial-level technology center	Equipment modernization; energy efficiency
Midstream: Reeling and weaving	Shuncheng Textile (顺成纺织)	Specialized silk reeling and textile manufacturing	Process optimization; waste reduction
Downstream: Garment manufacturing	Jiafeng Fashion (家丰时装)	Silk garment design and production	Green design; material efficiency; branding
Cross-cutting: By-product valorization	Multiple small and medium enterprises	Mulberry tea, mulberry fruit, silk protein products	Circular economy; agricultural carbon benefits
Cross-cutting: Cultural tourism	Nanchong Silk Culture Industrial Park; Langzhong Ancient City silk heritage sites	Silk museums, experiential workshops, heritage tourism	Dematerialized value creation; cultural preservation

3.3. Data Sources

All data used in this study are publicly available. The principal sources include the following categories.

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Government policy documents comprise the Nanchong Municipal 14th Five-Year Plan for Silk, Textile, and Garment Industry Development, the Nanchong Carbon Peaking Implementation Plan (January 2024), Sichuan Provincial policies on silk industry development and green manufacturing, and the national Green Manufacturing System guidelines issued by the Ministry of Industry and Information Technology[5].

Enterprise information is drawn from official websites of the selected enterprises, business registration records from the National Enterprise Credit Information Publicity System, press releases and media reports from Nanchong Municipal Government portals, and publicly disclosed investment project filings.

Industry association data include publications and statistical reports from the Nanchong Cocoon-Silk-Silk Association, the China Silk Association, and the Sichuan Provincial Silk Association.

Statistical data are sourced from the Nanchong Statistical Yearbook, the Nanchong Annual Statistical Communiqué of National Economic and Social Development (2020–2024), and the China Textile Industry Development Report.

Secondary academic literature includes recent empirical studies on textile industry carbon emissions, silk industry innovation networks, and green transformation of traditional industrial clusters[6].

3.4. Analytical Procedure

The analysis proceeds in three stages. First, we construct a qualitative carbon profile of each chain segment based on secondary data and literature, identifying the principal emission sources, carbon sink potentials, and resource consumption patterns. Second, we analyze each embedded case individually, examining the enterprise's low-carbon initiatives across the five analytical dimensions and identifying enabling factors and constraints. Third, we conduct cross-case analysis to identify patterns, complementarities, and gaps across the chain, synthesizing the findings into the integrated "Silk Green Chain" framework.[4]

4. Carbon Profile of Nanchong's Silk Industry Chain

4.1. Upstream: Sericulture as a Potential Carbon Sink

The upstream segment of Nanchong's silk chain encompasses mulberry tree cultivation, silkworm egg production, silkworm rearing, and fresh cocoon harvesting. This segment is fundamentally agricultural and biological in nature, and its carbon dynamics are qualitatively different from those of industrial processing[3].

Mulberry trees are fast-growing perennials that absorb CO_2 through photosynthesis and store carbon in their wood, roots, and leaf biomass. Under conventional management in Sichuan's subtropical climate, mulberry plantations achieve substantial annual biomass increments. When managed organically — without synthetic fertilizers, whose production is highly carbon-intensive — the net carbon balance of sericulture can be significantly favorable. Organic management substitutes biological nitrogen fixation, composting of silkworm waste (蚕沙), and mulberry branch recycling for synthetic inputs, simultaneously reducing upstream emissions and enhancing soil carbon sequestration[8].

Nanchong's sericulture base is concentrated in its rural counties — Nanbu, Yilong, Yingshan, Peng'an, and Xichong — where mulberry cultivation is deeply embedded in the agrarian landscape and cultural identity. The Litai Fung Group has developed 16,000 mu (approximately 1,067 hectares) of organic sericulture base in Yilong County, representing one of the largest certified organic silk raw material sources in China. This investment demonstrates that large-scale organic sericulture is commercially viable when integrated with downstream demand from eco-conscious international buyers.

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However, conventional sericulture in Nanchong still relies partially on chemical fertilizers for mulberry cultivation and on coal or biomass-fired heating for silkworm rearing rooms during cooler months. The carbon reduction potential of the upstream segment therefore depends critically on the pace of organic conversion and the adoption of clean heating technologies[9].

4.2. Midstream: The Emission Hotspot

The midstream segment — encompassing cocoon drying, silk reeling, degumming, throwing, weaving, and especially dyeing and finishing — is the carbon-intensive core of the silk chain. Our qualitative assessment, triangulated with published textile industry energy data, identifies four principal emission hotspots within this segment.

The first hotspot is cocoon drying and reeling. Fresh cocoons must be dried to kill the chrysalis and preserve silk quality before reeling. Traditional drying methods use coal-fired or gas-fired ovens, consuming significant thermal energy. The reeling process itself requires heated water baths to soften the sericin coating before unwinding the silk filament.[7]

The second hotspot is degumming. Raw silk contains 20–30% sericin (silk glue) by weight, which must be removed through boiling in soap or alkaline solutions. This process is both energy-intensive (requiring sustained boiling temperatures) and chemically intensive (generating alkaline wastewater).

The third and most significant hotspot is dyeing and finishing. Conventional silk dyeing uses synthetic dyes and chemical auxiliaries, requires large volumes of heated water, and generates colored, chemically laden effluent. Finishing processes — including softening, anti-wrinkle treatment, and waterproofing — add further chemical and energy inputs.

The fourth hotspot is weaving. While mechanized weaving is less energy-intensive per meter than dyeing, the aggregate energy consumption is significant given the volume of fabric produced. Older shuttle looms consume substantially more energy per unit output than modern rapier or air-jet looms.

For Nanchong specifically, the midstream segment's carbon intensity is exacerbated by the vintage of much of the city's processing equipment. While leading enterprises like Yiger Textile have invested in modernization, many small and medium-sized reeling and weaving operations continue to use equipment dating from the 1990s or earlier, with correspondingly lower energy efficiency[8].

4.3. Downstream: Lower Intensity, Higher Leverage

The downstream segment — garment design, pattern cutting, sewing, finishing, and packaging — is the least carbon-intensive segment per unit of value added. Sewing operations are primarily electricity-driven, and their energy consumption is modest compared with thermal processes upstream. However, the downstream segment exercises disproportionate leverage over the entire chain's carbon performance through two mechanisms.[4]

The first mechanism is demand signaling. When downstream brands and buyers require eco-certified raw materials and processing, they create market incentives for upstream and midstream operators to invest in green upgrading. The Litai Fung Group's insistence on organic sericulture and EU-standard environmental performance in its Yilong industrial park illustrates this demand-pull effect.[9]

The second mechanism is value capture. By successfully branding silk products as sustainable, organic, or heritage-certified, downstream enterprises can capture price premiums that cross-subsidize the higher costs of green production throughout the chain. Without such premium pricing, the economic case for midstream clean production investments is often marginal for small producers.[5]

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4.4. Cross-Cutting: By-Product Valorization and Cultural Tourism

Two cross-cutting activities span the entire chain and offer significant low-carbon co-benefits.

Comprehensive utilization of sericulture by-products is the first. The silk production process generates numerous by-products that are traditionally discarded or undervalued: mulberry leaves and fruit (edible and medicinal), mulberry branches (biomass fuel or mushroom cultivation substrate), silkworm excrement (organic fertilizer or traditional Chinese medicine raw material), silk waste and short fibers (silk protein extraction for cosmetics and biomaterials), and sericin recovered from degumming wastewater (pharmaceutical and cosmetic applications). Valorizing these by-products creates a circular economy loop that reduces waste, generates additional revenue, and displaces carbon-intensive alternative products.[3]

Cultural tourism integration is the second cross-cutting activity. Nanchong's designation as "China's Silk Capital" and "Origin of Silk" provides a powerful cultural brand that can be monetized through experiential tourism — silk museums, artisanal weaving workshops, mulberry garden agritourism, and Silk Road cultural festivals. This represents a form of "dematerialized value creation" that generates economic returns with minimal additional carbon emissions, effectively decoupling revenue growth from emission growth.[3]

5. Case Analysis: Low-Carbon Upgrading Strategies across the Chain

5.1. Case 1: Bubisi Organic Agriculture — Upstream Carbon Sink Creation

Bubisi (布碧丝) Organic Agriculture represents the upstream frontier of Nanchong's silk chain green transformation. The enterprise specializes in organic mulberry cultivation and silkworm rearing, operating without synthetic pesticides, herbicides, or chemical fertilizers[2].

Across the five analytical dimensions, Bubisi's contributions are concentrated in organic raw material substitution and by-product valorization. By eliminating synthetic agrochemical inputs, the enterprise avoids the embedded carbon emissions associated with fertilizer production (the Haber-Bosch process for nitrogen fertilizer is among the world's most energy-intensive industrial processes)[7]. Simultaneously, organic management practices — including composting of silkworm excrement, green manuring between mulberry rows, and retention of mulberry prunings as soil organic matter — enhance soil carbon stocks, contributing to a net carbon sink function.

The by-product dimension is also significant. Organic mulberry leaves are harvested not only for silkworm feed but also for mulberry leaf tea, a health product with growing market demand in China. Organic mulberry fruit is processed into juice, wine, and dried snacks. These diversified revenue streams improve the economic viability of organic sericulture, which typically yields lower cocoon volumes per hectare than conventional management but commands higher prices per kilogram.

The enabling factors for Bubisi's model include the growing domestic and international market demand for certified organic silk products, Nanchong's favorable climate for mulberry cultivation (subtropical, with adequate rainfall and mild winters), and policy support from both the Nanchong Municipal Government and the Sichuan Provincial agricultural authorities for organic agriculture conversion.[8]

The constraints include the relatively long conversion period from conventional to certified organic status (typically three years), the higher labor costs of organic management (organic sericulture is more labor-intensive than conventional practice), and the limited premium that domestic markets currently offer for organic silk cocoons compared with conventional cocoons.

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5.2. Case 2: Litai Fung Group / Yilong Eco-Industrial Park — Full-Chain Integration

The Hong Kong-based Litai Fung Group's investment in Yilong County represents the most ambitious full-chain green integration project in Nanchong's silk industry. The group has constructed a garment manufacturing industrial park built to standards exceeding European Union environmental requirements, while simultaneously developing 16,000 mu of organic sericulture base to supply certified raw materials.

This case is distinctive in its full-chain scope. Rather than addressing individual segments in isolation, Litai Fung has created an integrated system in which organic upstream production, environmentally controlled midstream processing, and export-oriented downstream manufacturing are coordinated under a single governance structure.[4] The park's environmental standards encompass wastewater treatment (achieving discharge standards stricter than Chinese national standards), energy efficiency (incorporating solar water heating and energy-efficient lighting throughout the facility), and waste management (segregation and recycling of textile waste, packaging materials, and organic residues).

The driving force behind this investment is market-driven: Litai Fung's principal customers are European and American fashion brands with stringent sustainability requirements and supply chain due diligence obligations. The EU Strategy for Sustainable and Circular Textiles (2022) and proposed EU Corporate Sustainability Due Diligence Directive create regulatory incentives for brands to source from verified sustainable suppliers, and Litai Fung has positioned its Yilong operation to meet these requirements.

The implications for Nanchong's broader silk industry are twofold. First, the Litai Fung model demonstrates that internationally competitive green silk production is technically and commercially feasible in Nanchong. Second, it creates a "demonstration effect" — a visible, successful example that can influence other local enterprises and attract additional green investment.[10] However, the model's replicability is limited by its reliance on a large Hong Kong-based corporate investor with international market access and substantial capital resources — conditions that most local small and medium enterprises cannot replicate independently.

5.3. Case 3: Yiger Textile — Midstream Equipment Modernization

Sichuan Yiger Textile Co., Ltd. (依格尔纺织) is one of Nanchong's leading silk reeling and weaving enterprises, operating a provincial-level technology center and producing a range of silk fabrics for both domestic and export markets.[10]

Yiger's low-carbon upgrading strategy is centered on the intelligent equipment dimension. The enterprise has invested in replacing older-generation reeling equipment with automated, computer-controlled reeling machines that achieve higher silk yield per kilogram of cocoons (reducing waste) and lower energy consumption per unit of output (through optimized motor control, heat recovery, and reduced downtime). In the weaving segment, the transition from shuttle looms to rapier looms has reduced per-meter energy consumption while simultaneously improving fabric quality and reducing noise pollution.

The enterprise has also made investments in the clean production dimension, including upgrading its dyeing facilities with lower-liquor-ratio dyeing machines that consume less water and energy per kilogram of fabric, and installing wastewater treatment systems that meet provincial discharge standards. However, a full transition to plant-based or low-impact dyes — which would represent a more fundamental shift in dyeing technology — has not yet been achieved, reflecting both the higher cost of alternative dyes and the technical challenges of achieving consistent color fastness on silk using non-conventional dyeing methods.[10]

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The enabling factors for Yiger's upgrading include its relatively large scale (which justifies capital investment in new equipment), its access to provincial-level technology center resources, and its exposure to export markets where environmental compliance is increasingly a precondition for market access. The principal constraint is the significant capital expenditure required for equipment replacement, which creates a financial barrier that smaller competitors cannot easily overcome.

5.4. Case 4: Shuncheng Textile — Process Optimization in Constrained Conditions

Shuncheng Textile (顺成纺织) represents a more typical midstream enterprise — smaller in scale than Yiger, with more limited capital resources, but still engaged in meaningful process optimization for energy and resource efficiency.[11]

Shuncheng's approach illustrates what might be called "incremental green upgrading" — improvements achieved not through wholesale equipment replacement but through better management of existing processes. Measures include optimized scheduling of energy-intensive operations to take advantage of off-peak electricity rates (reducing cost and, in systems with time-varying carbon intensity, potentially reducing emissions), improved maintenance protocols that reduce energy waste from poorly functioning equipment, and water recycling systems that reduce both water consumption and wastewater treatment costs.[4]

This case is analytically important because it represents the reality facing the majority of Nanchong's silk processing enterprises — firms that lack the capital for transformative equipment upgrades but can nonetheless achieve meaningful emission reductions through operational improvements. The policy implication is that green transformation support for the silk industry should include not only subsidies for major equipment purchases but also technical assistance programs for process optimization, energy auditing, and management training targeted at small and medium enterprises.

5.5. Case 5: Jiafeng Fashion — Downstream Green Design and Branding

Jiafeng Fashion (家丰时装) operates in the downstream garment manufacturing segment, where it designs and produces silk garments for both domestic and international markets.

Jiafeng's low-carbon relevance lies primarily in the cultural-tourism and branding dimension, combined with material efficiency improvements. The enterprise has adopted lean cutting techniques that minimize fabric waste (cutting losses in garment manufacturing can range from 10–25% of input fabric, and even modest reductions translate into significant material and embedded-carbon savings across the chain). It has also invested in design strategies that emphasize durability and timelessness over seasonal fashion cycles, aligning with the "slow fashion" movement that reduces the lifecycle carbon footprint of garments by extending their useful life.[11]

Jiafeng's branding strategy increasingly incorporates Nanchong's "China's Silk Capital" designation and the cultural heritage narrative of the Silk Road, positioning its products as premium, sustainable, and culturally authentic. This cultural branding approach enables higher price points that reflect the true cost of sustainable production, helping to overcome the "green premium" barrier that discourages consumers from choosing environmentally superior but more expensive products.

5.6. Cross-Cutting Case: Sericulture By-Product Enterprises

Multiple small and medium enterprises in Nanchong's silk cluster are engaged in the valorization of sericulture by-products, collectively constituting a nascent circular economy ecosystem.[8] Products include mulberry leaf tea (桑叶茶), which is marketed as a health beverage with properties supporting blood sugar regulation; mulberry fruit wine and juice;

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dried mulberry fruit snacks; organic fertilizer derived from silkworm excrement; and silk amino acid extracts for cosmetic applications.

The carbon reduction logic of by-product valorization operates through substitution effects. When mulberry fruit replaces conventionally grown fruit in consumer markets, the net carbon impact depends on the comparative land-use efficiency and input intensity of the two production systems. When silkworm excrement replaces synthetic fertilizer, the carbon savings are substantial given the high embodied energy of chemical fertilizer production. When silk protein extracts substitute for petroleum-derived cosmetic ingredients, the lifecycle carbon benefit is likely positive.[11]

However, the by-product sector in Nanchong remains fragmented, small-scale, and poorly integrated with the mainstream silk value chain. Most by-product enterprises operate independently, without formal coordination with upstream sericulture operations or midstream processing facilities. Realizing the full circular economy potential requires institutional mechanisms — such as cluster-level waste exchange platforms, shared processing facilities for by-product extraction, and coordinated marketing under a unified "Nanchong Silk" brand — that currently exist only in embryonic form.

5.7. Cross-Cutting Case: Silk Cultural Tourism

Nanchong has made significant investments in silk-themed cultural tourism, leveraging its historical designations and tangible heritage assets. The Nanchong Silk Culture Industrial Park serves as a combined museum, exhibition center, and experiential production facility where visitors can observe silk reeling and weaving processes, participate in hands-on workshops, and purchase silk products directly. Langzhong Ancient City, a nationally designated historical and cultural city within Nanchong's jurisdiction, incorporates silk heritage elements into its broader cultural tourism offering.[11]

From a low-carbon perspective, cultural tourism represents the most "dematerialized" form of value creation in the silk chain. Each tourist visit generates revenue that is attributed to the silk industry's economic output but involves negligible additional material throughput or industrial emissions. The principal carbon costs are transportation-related (visitor travel to Nanchong), which are largely outside the industry's control but can be mitigated through regional tourism circuit design that integrates silk tourism with other attractions (Langzhong Ancient City, Zhu De's birthplace in Yilong, the Jialing River scenic corridor) to maximize visitor time and spending per trip.[10]

Moreover, cultural tourism performs an essential narrative function: it tells the story of silk's origin, craftsmanship, and sustainability to consumers, creating emotional connections that support premium pricing and brand loyalty for Nanchong silk products. This narrative infrastructure is a "soft" but strategically important component of the green transformation, because consumer willingness to pay for sustainable products is strongly influenced by the authenticity and emotional resonance of the sustainability story.

6. Cross-Case Synthesis: The "Green Sandwich" Pattern and the "Silk Green Chain" Framework

6.1. The "Green Sandwich" Pattern

Cross-case analysis reveals a distinctive pattern that we term the "green sandwich." The upstream (sericulture) and downstream (garment manufacturing and branding) segments of the silk chain are relatively amenable to low-carbon upgrading: organic sericulture can achieve net carbon sink status, while downstream enterprises can pursue green design, material efficiency, cultural branding, and dematerialized value creation with manageable investment requirements.[5]

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The midstream segment — reeling, degumming, weaving, and especially dyeing and finishing — is "sandwiched" between these greener extremes and constitutes the principal barrier to full-chain decarbonization. This segment faces the highest technical complexity (dyeing chemistry, water treatment, thermal process optimization), the highest capital requirements (equipment replacement, effluent treatment plant construction), and the lowest ability to capture green price premiums (midstream products are intermediate goods whose environmental attributes are invisible to final consumers unless certified and communicated by downstream brands).[8]

The "green sandwich" pattern has important implications for policy design. If green transformation support is concentrated only on the most visible segments — upstream organic farming and downstream branding — the midstream bottleneck will persist, and the chain as a whole will fail to achieve meaningful decarbonization. Conversely, forcing midstream enterprises to bear the full cost of green upgrading without addressing market failures in green premium transmission will drive small producers out of business, undermining the cluster's scale and employment base.

6.2. The "Silk Green Chain" Framework

Based on our cross-case synthesis, we propose an integrated "Silk Green Chain" (丝绸绿链) framework for the holistic green transformation of traditional silk industry clusters. The framework consists of five interconnected pillars.

Pillar 1: Organic Foundation. Systematic conversion of the sericulture base to certified organic management, creating both a carbon sink function and a certified raw material supply that enables downstream eco-branding. The organic conversion should be supported by transitional subsidies, technical training for farmers, and group certification schemes that reduce per-farm certification costs.

Pillar 2: Digital Lean Processing. Investment in intelligent manufacturing equipment and digital process control systems across the midstream segment, targeting the principal emission hotspots: cocoon drying (switching from coal/gas to electric or solar thermal systems), degumming (adopting enzymatic or ultrasonic degumming technologies that reduce chemical and energy inputs), weaving (transitioning to energy-efficient loom technologies), and dyeing and finishing (implementing low-liquor-ratio dyeing, cold-pad-batch dyeing, and digital printing technologies). This pillar requires the most significant capital investment and should be supported by green finance instruments, equipment subsidy programs, and shared-facility models for smaller enterprises.

Pillar 3: Clean Chemistry. A targeted transition in dyeing and finishing from conventional synthetic dyes and chemical auxiliaries toward lower-impact alternatives: natural dyes derived from local botanical sources (Sichuan is rich in dyestuff plants), bio-based auxiliaries, and closed-loop water recycling systems that minimize effluent discharge. This pillar is the most technically challenging and will require sustained R&D investment and collaboration with textile research institutes.

Pillar 4: Circular Valorization. Systematic development of the sericulture by-product economy, transforming waste streams into value streams: mulberry leaf tea and fruit products, silk protein extracts, organic fertilizer from silkworm waste, and biomass energy from mulberry prunings. This pillar should be organized through cluster-level coordination mechanisms — waste exchange platforms, shared processing facilities, and a unified "Nanchong Silk Circular" brand — rather than left to individual enterprise initiative alone.

Pillar 5: Cultural Premium. Strategic development of the "China's Silk Capital" and "Origin of Silk" cultural brands as vehicles for green premium capture, encompassing eco-labeling and certification (organic, fair trade, carbon-neutral), heritage storytelling and provenance marketing, experiential cultural tourism, and design collaborations with national and

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international fashion houses that amplify Nanchong's sustainability narrative. This pillar is the mechanism through which the costs of the other four pillars are recovered and the economic sustainability of green transformation is secured.

The five pillars are interdependent. Organic Foundation (Pillar 1) provides the certified raw materials that underpin Cultural Premium (Pillar 5); Digital Lean Processing (Pillar 2) reduces the cost structure that would otherwise make green production uncompetitive; Clean Chemistry (Pillar 3) eliminates the environmental externalities that would undermine the credibility of eco-certification; and Circular Valorization (Pillar 4) generates supplementary revenue that cross-subsidizes investment in the other pillars.

7. Discussion

7.1. Theoretical Implications

The "green sandwich" pattern identified in this study adds nuance to the ecological modernization literature. While ecological modernization theory broadly predicts that technological innovation can reconcile economic growth with environmental improvement, our chain-level analysis reveals that the feasibility and cost of this reconciliation vary dramatically across chain segments. The pattern suggests that ecological modernization in traditional industries requires chain-level coordination — not merely individual firm-level innovation — to overcome the structural disadvantage of midstream processors who bear the highest upgrading costs but capture the lowest share of green value.

The "Silk Green Chain" framework also extends the global value chain (GVC) upgrading literature by demonstrating how environmental upgrading can be intertwined with functional upgrading (moving from low-value-added processing to higher-value-added branding and design) and product upgrading (shifting from commodity silk products to certified, premium offerings)[12]. This triple-upgrading dynamic is characteristic of traditional industries with strong cultural heritage assets — a category that includes not only silk but also tea, ceramics, lacquerware, and other artisanal manufacturing sectors throughout Asia.[13]

7.2. The Role of External Demand as a Green Transformation Driver

A striking finding across our cases is the catalytic role of international market demand in driving green upgrading. The Litai Fung Group's Yilong investment is explicitly motivated by European buyers' sustainability requirements; Yiger Textile's equipment modernization is partly driven by export market environmental compliance standards; and the organic sericulture movement draws significant impetus from the premium prices that certified organic silk commands in Japanese and European markets[14].

This demand-pull mechanism has important policy implications. Nanchong's silk industry cannot achieve green transformation solely through supply-side technology push; it also requires strategic market positioning that connects local production with the growing global demand for sustainable textiles. [15]The city's "14th Five-Year Plan for Silk" acknowledges this logic by emphasizing the goal of building a "national silk, textile, and garment center city" with international market orientation. However, most small and medium enterprises in the cluster lack direct access to international markets and depend on trading intermediaries who may not transmit sustainability price premiums effectively. Strengthening market access for sustainable silk — through trade fair participation, e-commerce platforms, and direct buyer-supplier matching — is therefore a critical complement to production-side green upgrading.

7.3. The Institutional Challenge of Cluster-Level Coordination

Several elements of the "Silk Green Chain" framework — particularly Circular Valorization and the shared infrastructure components of Digital Lean Processing — require collective action at

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the cluster level rather than individual enterprise initiative. The establishment of waste exchange platforms, shared dyeing and finishing facilities with advanced environmental controls, and unified brand management systems all constitute public or club goods that face familiar collective action problems: free-riding, coordination costs, and distributional conflicts over cost sharing.

In Chinese industrial clusters, local government typically plays the coordinating role, using a combination of planning guidance, infrastructure investment, and regulatory enforcement to overcome collective action failures. Nanchong's municipal government has demonstrated institutional commitment through the "14th Five-Year Plan for Silk" and the Carbon Peaking Implementation Plan, both of which identify the silk industry as a priority sector for green transformation.[16] However, the translation of planning intent into effective cluster-level coordination remains a governance challenge, particularly given the fragmented structure of the midstream processing segment (many small enterprises with limited individual bargaining power or investment capacity).

The Nanchong Cocoon-Silk-Silk Association and other industry associations could play a more active intermediary role — facilitating joint environmental audits, coordinating shared facility investments, negotiating group procurement of green equipment, and administering cluster-level eco-certification. Strengthening the institutional capacity of these associations is an underappreciated but potentially high-leverage policy intervention.

7.4. Green Transformation as Heritage Preservation

An underexplored dimension of our analysis is the relationship between green transformation and cultural heritage preservation. Nanchong's silk industry is not merely an economic activity but a cultural practice with roots extending over two millennia. The designation of Nanchong as "China's Silk Capital" and "Origin of Silk" reflects official recognition of this cultural significance.

Green transformation, paradoxically, may be the most effective strategy for heritage preservation. Without upgrading, Nanchong's silk industry faces a future of declining competitiveness, youth out-migration from sericulture communities, and gradual erosion of craft knowledge. Green transformation — by creating premium market positions, diversifying revenue streams through by-product valorization and cultural tourism, and modernizing production conditions to attract younger workers — can revitalize the industry economically while maintaining its cultural continuity.

Conversely, heritage assets — artisanal skills, historical narratives, geographic identity — are powerful enablers of green transformation because they provide the authenticity and emotional resonance that justify premium pricing for sustainable products. This mutually reinforcing relationship between green upgrading and heritage preservation is a distinctive advantage of traditional industry clusters that heavy industries and high-tech sectors do not possess.

7.5. Limitations

This study has several limitations. First, the absence of primary quantitative data on enterprise-level energy consumption, carbon emissions, and financial performance means that our analysis of low-carbon upgrading strategies is necessarily qualitative and cannot quantify the precise emission reductions or cost-benefit ratios associated with specific interventions. Future research should conduct firm-level carbon audits and techno-economic assessments to complement the qualitative findings presented here.

Second, the embedded multi-case design, while analytically powerful for revealing chain-level patterns, is limited to a single silk cluster (Nanchong) and may not fully capture the diversity of green transformation experiences in other Chinese silk-producing regions (Jiangsu, Zhejiang,

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Guangxi). Comparative studies across multiple silk clusters would enhance the generalizability of the "green sandwich" pattern and the "Silk Green Chain" framework.

Third, our analysis relies on publicly available information, which may present an incomplete or positively biased picture of enterprise behavior (firms tend to publicize their environmental initiatives more readily than their environmental shortcomings). Primary interview data with enterprise managers, workers, sericulture farmers, and local officials would provide richer and more balanced insight into the enabling factors, constraints, and unintended consequences of green transformation in practice.

8. Policy Recommendations

Based on our analysis, we offer six integrated policy recommendations for Nanchong and for other traditional industry clusters pursuing green transformation.

First, adopt a chain-level green transformation strategy rather than a segment-by-segment approach. The "green sandwich" pattern demonstrates that the effectiveness of green upgrading at any single chain segment depends on complementary investments at other segments. Policy design should target the full chain, with differentiated instruments for each segment: organic conversion subsidies for upstream sericulture, equipment modernization grants and green finance for midstream processing, and market access support and branding investment for downstream manufacturing.

Second, prioritize the midstream bottleneck through shared green infrastructure. The most impactful — and most difficult — interventions are in the midstream dyeing and finishing segment. Nanchong should invest in shared, cluster-level dyeing and finishing facilities equipped with state-of-the-art clean production technologies, offering services to small and medium enterprises that cannot individually afford such investments. This "green commons" approach distributes the fixed costs of clean technology across many users and ensures uniform environmental performance across the cluster.

Third, accelerate organic sericulture conversion through transitional support. The three-year organic conversion period represents a financial barrier for sericulture farmers who face lower yields without yet qualifying for organic price premiums. Transitional income support payments, technical extension services, and group certification schemes can bridge this gap and accelerate the expansion of Nanchong's organic sericulture base.

Fourth, develop a unified "Nanchong Silk" eco-brand with international market orientation. The city's "China's Silk Capital" and "Origin of Silk" designations are powerful brand assets that are currently underutilized in international markets. A unified eco-brand — integrating organic certification, geographic indication, carbon footprint labeling, and heritage storytelling — would create a market identity that individual enterprises cannot build alone, enabling collective green premium capture.

Fifth, institutionalize circular economy coordination. By-product valorization should be elevated from an opportunistic activity of individual entrepreneurs to a systematically coordinated cluster function. Specific mechanisms should include a sericulture by-product exchange platform (connecting producers of mulberry leaves, fruit, branches, silkworm waste, and silk waste with processors and end-users), shared by-product processing facilities, and R&D partnerships with universities and research institutes for high-value applications of silk proteins and mulberry bioactive compounds.

Sixth, integrate silk cultural tourism into the green transformation narrative. Cultural tourism should be explicitly positioned as the fifth pillar of the silk industry's economic model, not as a peripheral add-on. Investment in silk museums, experiential workshops, heritage trails, and festival events should be coordinated with the industry's sustainability messaging, creating a

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virtuous cycle in which tourism generates both revenue and consumer awareness that supports demand for sustainable silk products.

9. Conclusion

This paper has examined the green transformation of Nanchong's silk industry — a complete traditional industry chain in a city officially designated as "China's Silk Capital" — through an embedded multi-case study design combined with an industry-chain life cycle analytical perspective. By analyzing representative enterprises across the upstream, midstream, and downstream segments of the silk value chain, we have identified the "green sandwich" pattern: the upstream (sericulture) and downstream (garment manufacturing and branding) segments possess inherent green endowments and relatively accessible upgrading pathways, while the midstream processing segment — particularly dyeing and finishing — constitutes the principal carbon emission hotspot and the most challenging upgrading bottleneck.

The "Silk Green Chain" framework proposed in this paper offers an integrated approach to overcoming this bottleneck through five interdependent pillars: organic foundation, digital lean processing, clean chemistry, circular valorization, and cultural premium. The framework recognizes that green transformation of a traditional industry chain is not merely a technical challenge but a systemic one, requiring chain-level coordination, cluster-level institutional innovation, and strategic market positioning.

Three broader insights emerge from this analysis. First, traditional industries are not inherently resistant to low-carbon transformation; they possess distinctive green endowments — biological raw materials, cultural heritage, artisanal identity — that can be leveraged for competitive advantage in an increasingly sustainability-conscious global market. Second, the chain-level perspective is essential for understanding and designing green transformation in traditional industries, because carbon intensity, upgrading feasibility, and value capture capacity vary dramatically across chain segments. Third, green transformation and cultural heritage preservation are not competing objectives but mutually reinforcing strategies: sustainability enhances heritage value, and heritage enables sustainability premiums.

As China pursues its dual-carbon goals, the fate of its traditional industries will depend on whether policymakers, enterprises, and communities can harness these synergies. Nanchong's silk industry — with its millennial heritage, complete value chain, and emerging green transformation initiatives — provides both a laboratory for experimentation and a model for emulation. The "Silk Green Chain" framework offers a roadmap, but its successful implementation will require sustained commitment, creative financing, and above all, the recognition that in the green economy, tradition is not a constraint but a resource.

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