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Innovative Plant-Dyed Silk Textiles: Does Intangible Cultural Heritage Matter? A Trajectory Equifinality Model

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Abstract

Natural silk textiles are regarded as integral components of cultural heritage, historically embedded within centuries of sericulture, natural dyeing, and communal weaving. The preservation of intangible cultural heritage in northeast Thailand is investigated through natural sericulture, plant-dyed silk—frequently produced with Indigofera tinctoria—and recent dyeing innovations. A qualitative methodology was employed, guided by the trajectory equifinality model (TEM). Interviews were undertaken with fifteen women weavers from Maha Sarakham Province. Through TEM analysis, four thematic domains were identified: natural sericulture, plant-dyed silk, dyeing innovations, and intangible cultural heritage (ICH). Plant-dyed silk textile production, sustained by ecological sericulture and dyeing practices, was found to support the safeguarding and promotion of intangible cultural heritage. Heritage preservation in the region was demonstrated to be reinforced by sustainable sericulture and innovative plant-dyeing.

Keywords: plant-dyed textiles; innovation; natural silk; intangible cultural heritage; trajectory equifinality model

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1. Introduction

A transition towards sustainable textile production was documented across both the industrial and artisanal sectors [1]. Natural dye colourants were re-evaluated in contemporary scholarship as feasible alternatives to synthetic dyes. Their use was framed within environmental discourse, with a particular emphasis on effluent management and biodegradability [2]. Historic dyeing practices are defined by silk preparation, immersion dyeing, colour layering, oxidation and setting, rinsing, washing, and drying. The revival of these techniques was interpreted as a convergence of ecological imperatives and heritage preservation [3].

Sustainable plant-dyed silk textiles, frequently produced with Indigofera tinctoria, were analysed through the combined frameworks of technological innovation and ICH significance [4]. In recent scholarship, ICH has been reconceptualised as a dynamic and adaptive system contributing to a sustainable future rather than as a static repository of inherited knowledge [5]. Mechanisms of cultural transmission were identified as fundamental to the continuation of artisanal dyeing skills under pressure of industrial standardisation. The nexus between environmental sustainability and heritage value was delineated as a research domain in which historical continuity, material innovation, and socio-cultural meaning were demonstrated to converge [6].

The dyeing of silk with natural colourants has been practised for centuries across Asia. The use of botanical pigments to generate vivid and durable hues was recorded in very old sources [7]. These techniques were embedded within ritual, social, and economic life, thereby establishing their centrality to material culture. In Southeast Asia, silk dyeing was integrated into broader textile traditions distinguished by symbolic motifs, intricate weaving, and regional colour palettes [8]. The continuity of these practices was maintained through intergenerational transmission of knowledge and adaptation to local environmental conditions.

ICH was defined by Chami et al. [9] as the practices, knowledge, and skills acknowledged by communities as integral to cultural identity. When applied to textile production, this framework was employed to highlight the social value of craft techniques beyond their economic utility. The safeguarding of plant-dyed silk production was interpreted as a means of sustaining cultural continuity and reinforcing craft resilience in the face of industrial manufacturing [10]. Within this perspective, traditional dyeing practices were regarded not as fixed relics, but as adaptive cultural resources with environmental and social significance.

The regional focus was directed towards Thailand, where silk weaving was recognised as possessing both socio-economic and cultural significance [11]. Rural livelihoods were historically sustained by silk production as a source of household income and as a medium for articulating local identity [12]. Plant-dyed silk textiles were incorporated into ceremonial dress, temple offerings, and cultural festivals, thereby embedding them within communal life [13]. The preservation of these practices was associated with rural development policies, cultural tourism, and heritage branding [14]. Within this context, the intersection of ICH and sustainable production was examined to trace the pathways through which traditional knowledge adapted to contemporary pressures [15].

Research on textile heritage has been dominated by analyses of material properties and technical processes, while sociocultural dynamics and mechanisms of heritage transmission have remained comparatively underexplored [16]. In studies of plant-dyed silk, modern analytical characterisation has seldom been integrated with socio-cultural frameworks capturing lived contexts of production [17]. Although plant-dyed silk has been recognised as central to craft preservation, the empirical evidence concerning its survival and transformation within the ICH framework in Thailand is limited [18]. Consequently, understanding of how traditional knowledge systems adapt to contemporary pressures is restricted, and intersections between sustainability, cultural identity, and innovation have been insufficiently examined.

Maha Sarakham Province in northeast Thailand was identified as a cultural centre of silk weaving and natural dyeing traditions [12,19]. Traditional and innovative approaches to plant-based dyeing in silk textiles were systematically compared (Appendix A, Table A1), thereby providing the empirical foundation for both local and modern weaving practices. In rural districts, textile production was maintained as both an occupation and a communal cultural practice [20]. Silk weaving was embedded within agricultural rhythms, with seasonal cycles governing production and dyeing activities. Plant-based colourants were locally sourced, thereby reinforcing ecological knowledge and material self-sufficiency. The preservation of these practices was enabled through intergenerational apprenticeship, local cooperatives, and heritage promotion initiatives [21]. This integration of economic function, cultural expression, and environmental adaptation was positioned as central to community resilience and identity in the region.

The province was recognised as representative of broader Thai silk trends in heritage textile production, where rural economies, environmental adaptation, and cultural identity intersected [22]. Academic significance was established through the integration of

cultural heritage studies, textile technology, and sustainable design within a unified interdisciplinary framework [23]. The practical value was demonstrated by offering guidance for policymakers in heritage preservation and for artisans in reconciling tradition with innovation. The application of the TEM to heritage textiles was positioned as novel for its capacity to map multiple adaptive pathways, illustrating how traditional practices were found to persist, evolve, or merge with new socio-economic contexts [24,25].

The primary objective of this study was defined as the examination of interactions among natural sericulture, plant-dyed silk production, and innovations in natural dyeing in relation to the safeguarding and transmission of ICH in northeast Thailand. Empirical evidence was produced of the adaptation of traditional silk-dyeing knowledge under socio-economic, environmental, and cultural pressures. The influence of heritage values on the adoption of innovative dyeing techniques was assessed. The TEM was applied to identify bifurcation points (BFPs), including transitions from traditional to natural dyes, shifts from subsistence to commercial sericulture, and the adoption of modern marketing channels. Equifinality points (EFPs) were analysed as shared outcomes achieved through divergent pathways, including cultural sustainability, economic resilience, and intergenerational skill transmission. Material analysis was combined with socio-cultural inquiry, ensuring findings that were both measurable and relevant to the sustainability of heritage textile practices.

Research Questions

The gaps in the literature on innovation and the sustainability of intangible cultural heritage in plant-dyed natural silk textiles in northeast Thailand were addressed in this study by structuring the investigation around the following research questions:

QR1: What processes transmit traditional knowledge of natural sericulture and silk textile production in northeast Thailand?

QR2: What methods safeguard natural silk textiles in northeast Thailand through traditional knowledge of plant-based dyes?

QR3: What factors drive innovation in natural dyeing practices for silk-producing communities in northeast Thailand?

QR4: In what ways do innovations in naturally dyed silk textiles constitute an element of intangible cultural heritage in northeast Thailand?

2. Materials and Methods

2.1. TEM Design

A qualitative research design was adopted, guided by the TEM, to examine how artisans in northeast Thailand engaged in the preservation and innovation of plant-dyed natural silk textile traditions. The TEM was considered particularly appropriate for capturing complex and non-linear life courses, as it permitted the mapping of BFPs, moments of decision or external influence, and EFPs, shared outcomes attained through diverse pathways [26]. In-depth interviews, participant observation, and life-history narratives were employed to trace artisans' developmental trajectories, and the cultural, economic, and institutional contexts shaping their decisions were identified. Socio-cultural embeddedness and individual agency were emphasised, allowing both convergence and divergence in the sustaining of intangible cultural heritage to be examined. Through its application, the TEM was positioned to advance beyond descriptive accounts towards an explanatory framework capable of capturing the dynamic processes underlying heritage adaptation.

2.2. TEM Setting

This study was conducted in Maha Sarakham Province, northeast Thailand (Isan), a region recognised for its cultural heritage and long-standing traditions of plant-dyed natural silk textile production. The province was regarded as significant for its active artisan communities, educational institutions, and grassroots initiatives dedicated to preserving and revitalising local crafts. It was identified as an appropriate context for the application of the TEM, owing to the diversity of artisan experiences shaped by market exposure, government support, and generational knowledge transmission. The TEM was employed in this setting to map individual and collective trajectories, with BFPs identified in areas such as tourism engagement and digital marketing and EFPs observed in the sustaining of cultural identity through innovation. Maha Sarakham was thereby positioned as a promising context for examining the evolution of traditional textile practices under local and global influences.

2.3. TEM Participants

The participants were composed of local artisans, community leaders, cultural practitioners, government representatives, and other stakeholders engaged in the preservation and innovation of plant-dyed natural silk textiles in Maha Sarakham Province. Purposive sampling was employed to capture diverse trajectories, experiences, and decision-making processes relevant to the TEM framework [26]. The sample was constituted of elder weavers maintaining traditional techniques alongside younger generations introducing practices such as digital marketing, eco-fashion design, and product diversification. This diversity was regarded as enabling the identification of BFPs, critical moments of change or external influence, and EFPs, shared outcomes such as economic sustainability and cultural continuity.

A purposive sampling strategy was employed to select 15 participants situated across the plant-dyed silk value chain, including sericulturists, dyers, weavers, and cooperative leaders [27]. The inclusion parameters were defined to ensure that participants possessed direct, practice-based expertise in both traditional and contemporary dyeing techniques. Recruitment was facilitated through local heritage networks and community-based organisations, with representation secured from multiple districts in Maha Sarakham Province. In-depth interviews and life-history narratives were conducted to examine the personal, cultural, and socio-economic circumstances, thereby enabling the reconstruction of individual trajectories within the evolving domain of intangible cultural heritage. Profiles of the key informants are summarised in Table 1.

Table 1. Participant backgrounds.

ID	Age Group	Weaving Experience (Years)	Indigofera Tinctoria Used	Role in Community	Heritage Transmission Mode	TEM Mapping (SP/BFP/OPP/EP)
W1	35–44	12	Mangifera indica	Pattern innovator	Learned from mother	SP → BFP (introducing modern motifs)
W2	45–54	20	Caesalpinia sappan	Co-op committee	Learned from grandmother	SP → OPP (heritage quality certification)
W3	55–64	35	Garcinia mangostana	Master weaver	Temple-based apprenticeship	SP → EP (full traditional preservation)
W4	65+	48	Punica granatum	Cultural mentor	Learned in childhood	SP → BFP (tourist market adaptation)
W5	35–44	15	Caesalpinia sappan	Independent seller	Learned via village training	SP → OPP (new market entry)
W6	45–54	23	Butea monosperma	Design leader	Learned from aunt	SP → BFP (pattern diversification)
W7	55–64	31	Terminalia chebula	Dyeing instructor	Learned from parents	SP → OPP (training workshops)
W8	65+	46	Curcuma longa	Heritage keeper	Learned from elders	SP → EP (pure traditional path)
W9	45–54	19	Mangifera indica	Market liaison	Learned in cooperative	SP → BFP (urban retail connection)
W10	35–44	14	Punica granatum	Dye experimenter	Learned from mother	SP → BFP (colour fastness trials)
W11	55–64	33	Garcinia mangostana	Senior artisan	Learned from grandmother	SP → OPP (national competition entry)

Table 1. *Cont.*

ID	Age Group	Weaving Experience (Years)	Indigofera Tinctoria Used	Role in Community	Heritage Transmission Mode	TEM Mapping (SP/BFP/OPP/EP)
W12	45–54	21	Mahogany bark	Training mentor	Learned via co-op training	SP → BFP (export market readiness)
W13	35–44	10	Tamarind leaf	Young innovator	Learned from elders + online	SP → BFP (digital marketing adoption)
W14	65+	40	Indigofera tinctoria	Village elder	Learned in childhood	SP → EP (heritage continuity)
W15	45–54	18	Coconut husk	Dye process leader	Learned from peers	SP → OPP (supply chain adaptation)

Note: Weaving experience (years) in the dyeing process of natural silk production. SP = starting point; BFP = bifurcation point; OPP = obligatory passage point; EP = equifinality point.

2.4. TEM In-Depth Interview Questions

In-depth interview questions were formulated to elicit the participants' life histories, decision-making processes, and perspectives on sustaining and innovating ICH. In accordance with the TEM framework, the questions were structured to examine pivotal turning points, external determinants, and convergent outcomes within participants' cultural and economic trajectories [28]. The complete set of open-ended interview questions is presented in Table 2.

Table 2. In-depth open-ended interview questions.

Main Concepts	Probing Questions
Introduction	The researchers provided a welcome note, explained interview guidelines, and outlined the purposes of the interview.
General questions	Could you describe your background in innovating natural silk production?
Natural sericulture production	What importance does the sericulture plant hold in silk production? What types of silkworm-rearing houses are used in silk production? What is the standard procedure for operating a cocoon-processing unit?
Plant-dyed natural silk	In what ways does the composition of natural silk affect the uptake of natural dyes? What methods are used to apply and fix plant-based dyes on natural fibres? How are traditional and modern dyeing processes used to create plant-dyed natural silk?
Innovation of natural dyeing	How does the revival of natural dyeing practices drive innovation in silk textiles? How does the adoption of eco-friendly production methods demonstrate innovation in silk textile design and processing? What modern natural dye extraction techniques foster innovation in silk textile design? In what ways do innovative dyeing methods foster advancements in silk textile production?
Intangible cultural heritage	Could you describe your background in innovating natural silk production? What traditional weaving methods and skills contribute to the preservation of intangible cultural heritage? What symbols and motifs are embodied in the intangible cultural heritage of traditional weaving? What role do adaptations and innovations play in preserving intangible cultural heritage? What cultural and ritual roles do intangible cultural heritage practices serve? How does intangible cultural heritage contribute to local identity and the economy?

2.5. TEM Analyses

The data analysis process was guided by the principles of the TEM, which was designed to trace and compare diverse life paths within shared socio-cultural contexts [29]. Interview transcripts and observational notes were transcribed, coded, and thematically categorised through qualitative content analysis, with attention directed to the identification of BFPs, moments of significant decision or change, and EFPs, shared outcomes such as cultural continuity and economic sustainability [26]. The data were then organised into life course maps or trajectory charts, visually representing each participant's developmental path and illustrating the intersection of external influences (e.g., government policies and market trends) with internal motivations (e.g., personal values and cultural pride). Cross-case comparisons were facilitated, enabling the identification of common

patterns and variations in artisan adaptation and innovation, while sustaining intangible cultural heritage. Through this process, the TEM was applied as a contextualised, process-oriented framework that advanced beyond static portrayals of tradition towards a dynamic understanding of cultural sustainability.

2.6. TEM Triangulation

To ensure the credibility and validity of the findings, data triangulation was employed through the integration of multiple sources and methods of collection, in line with best practices in qualitative research [30]. The primary data were gathered through in-depth interviews, participant observation, and life-history narratives with the artisans and stakeholders engaged in plant-dyed silk textile practices in Maha Sarakham Province. These were supplemented by documentary analysis of local policies and archival materials relating to cultural heritage preservation. Triangulation across these sources was regarded as facilitating a deeper understanding of the contextual and structural factors shaping artisan trajectories, while supporting the TEM by validating critical BFPs and EFPs identified in participant narratives [26]. This layered approach was considered to have strengthened the reliability and depth of analysis, ensuring that evolving cultural practice pathways were interpreted from multiple perspectives.

3. Findings

3.1. Development of Initial Coding, Thematic Grouping, and Emerging Theory

Using the TEM to analyse the dataset, initial coding was undertaken to identify the material, technical, and cultural components underpinning natural sericulture, plant-dyed silk processes, innovations in natural dyeing, and intangible cultural heritage. Thematic grouping was then applied to organise these codes into interconnected domains: production infrastructure (mulberry cultivation, silkworm rearing, and cocoon processing); material–process integration (natural silk bases, plant-based dyes, and dyeing sequences); innovation and sustainability (revival of local dyes, eco-friendly methods, modern extraction, and fusion design); and heritage and identity (weaving skills, motifs, ritual significance, and the local economy).

Within the TEM, these domains were interpreted as equifinality points, where the pathways originating in traditional practices, market-driven modernisation, or eco-conscious initiatives converged towards the shared outcome of sustaining and evolving natural silk textile heritage. An emerging theory was advanced that sericulture and dyeing should be understood not as linear craft processes, but as dynamic, culturally embedded systems in which innovation and preservation operated as parallel trajectories, with BFPs shaped by ecological resources, intergenerational knowledge transfer, and socio-economic drivers. Natural silk production was therefore positioned as a living practice in which tradition and innovation functioned as mutually reinforcing pathways leading to cultural resilience. The themes, categories, and coding derived from the TEM process are presented in Table 3.

3.2. Code Saturation and Theme Development

Using the TEM as a framework, code saturation was judged to have been achieved when recurring themes consistently emerged across the interviews and the field observations concerning natural sericulture, plant-dyed silk practices, and heritage innovation. Several BFPs were identified, including transitions from traditional to natural dyes, shifts from subsistence to commercial sericulture, and the choices between traditional and modern marketing channels. These BFPs were interpreted as reflections of critical decisions made by artisans in response to external influences such as globalisation, market pressures, and government intervention.

Table 3. Themes, categories, coding framework, and meanings.

Theme	Category	Coding	Meaning/Interpretation
Natural sericulture production	Sericulture plant	Participants stated that natural sericulture plays a central role in silk textile production. • Mulberry cultivation unit • Land for mulberry farming • Irrigation systems • Nursery area • Compost unit • Storage shed	Natural sericulture production was shown to integrate mulberry cultivation, irrigation, nurseries, composting, and storage to sustain plant-dyed silk textiles as a living form of intangible cultural heritage.
	Silkworm rearing house	Participants stated that natural sericulture production is associated with the silkworm-rearing house in silk textile production. • Rearing trays/racks • Controlled environment • Disinfection room • Mountages	Silkworm-rearing houses were shown to employ trays, controlled environments, disinfection rooms, and mountages to transform raw cultivation into viable silk that embodied cultural heritage.
	Cocoon processing unit	Participants stated that natural sericulture production is associated with the cocoon-processing unit in silk textile production. • Cocoon drying/stifling chamber • Sorting and grading table • Storage room	Cocoon processing units were shown to apply drying, grading, and storage to secure silk quality and preserve its role as cultural heritage.
Plant-dyed natural silk	Natural silk base	Participants stated that plant-dyed natural silk is associated with the natural silk base used in textile production. • Mulberry silk (Bombyx mori) • Eri silk (Samia ricini) • Tussar silk (Antheraea mylitta) • Muga silk (Antheraea assamensis)	Plant-dyed textiles were shown to draw on mulberry, eri, tussar, and muga silks to anchor material diversity within the framework of intangible cultural heritage.
	Plant-based dyes	Participants revealed that plant-dyed natural silk incorporates gradient colour palettes in textile production. • Deep burgundy • Violet/purple • Rust-orange	Plant-based dyes were shown to infuse natural silk with burgundy, violet, and rust-orange tones, creating gradient palettes that embodied intangible cultural heritage.
	Dyeing process	Participants stated that plant-dyed natural silk is associated with the dyeing process used in silk textile production. • Scouring the silk • Mordanting • Dye extraction • Dyeing the silk • Rinsing and drying	The dyeing process was shown to scour, mordant, extract, apply, and rinse plant dyes on silk to secure chromatic depth and sustain intangible cultural heritage.
	Revival natural dyeing practice	Participants identified the use of local plant materials to revive natural dyeing practices in silk textile production. • Indigo • Jackfruit wood • Sappanwood • Mangosteen rind • Pomegranate peel	The revival of natural dyeing was shown to innovate with indigo, jackfruit wood, sappanwood, mangosteen rind, and pomegranate peel to renew colour traditions and reinforce intangible cultural heritage.
Innovation of natural dyeing	Eco-friendly textile production	Participants stated that eco-friendly textile production promotes the production of natural silk textiles. • Skill training in dyeing • Intergenerational learning	Eco-friendly textile production was shown to advance through dyeing skill training and intergenerational learning to foster sustainable practice and strengthen intangible cultural heritage.
	Modern extraction techniques	Participants categorised innovations in natural dyeing as the development of modern extraction techniques in silk textiles. • Drying and grinding • Extraction method • Dyeing the silk • Post-dye treatment • Finishing and quality control	Modern extraction techniques were shown to apply drying, grinding, extraction, dyeing, post-dye treatment, and finishing to enhance silk quality and reinforce intangible cultural heritage.
	Innovative dyeing practice	Participants reported that innovative dyeing practices facilitate the integration of traditional weaving in silk textiles. • Colour layering techniques • Modern design patterns • Fashion collaboration • Skill training in dyeing • Intergenerational learning	Innovative dyeing practices were shown to employ colour layering, modern design patterns, fashion collaboration, skill training, and intergenerational learning to expand creative expression and sustain intangible cultural heritage.

Table 3. *Cont.*

Theme	Category	Coding	Meaning/Interpretation
Intangible cultural heritage	Weaving techniques and skills	Participants stated that weaving techniques and skills ground intangible cultural heritage in natural silk textiles. • Twining and brocade techniques • Reed and heddle setup skills • Colour blending through thread selection • Finishing techniques • Pattern memorization • Traditional wooden looms	Weaving traditions were shown to employ twining, brocade, reed and heddle setup, colour blending, finishing, pattern memorisation, and wooden looms to transmit technical skill and preserve intangible cultural heritage.
	Design motifs and symbolism	Participants reiterated that intangible cultural heritage is associated with the design motifs and symbolism embedded in natural silk textiles. • Diamond motif • Khid patterns • Lotus flower • Cocoon patterns	Design traditions were shown to employ diamond, khid, lotus, and cocoon motifs to encode symbolism that sustains intangible cultural heritage.
	Adaptation and innovation	Participants outlined how intangible cultural heritage is embedded in processes of adaptation and innovation in natural silk textiles. • Blending traditional and modern motifs • Natural dye enhancement • Eco-conscious dyeing practices • Digital and social media marketing • Community-based branding	Heritage adaptation was shown to advance through natural dye enhancement, eco-conscious practices, digital marketing, and community branding to secure cultural relevance and sustain intangible cultural heritage.
	Cultural and ritual significance	Participants narrated the cultural and ritual significance of intangible cultural heritage in natural silk textiles. • Ceremonial dress in Buddhist rituals • Traditional wedding attire • Festival and cultural identity display • Sacred symbolism in motifs • Textiles in funerals and memorials	Textile traditions were shown to embody ceremonial dress, wedding attire, festival display, sacred motifs, and funerary use, thereby affirming cultural identity and preserving intangible cultural heritage.
	Local identity and regional economy	Participants discussed the relationship between intangible cultural heritage, cultural identity, and the economic life of the local area. • Integration in local dress • Women's economic empowerment • Cultural and creative industries growth	Plant-dyed silk was shown to be integrated into local dress, to empower women, and to drive cultural industries that reinforce regional economies and sustain intangible cultural heritage.

EFPs such as the preservation of cultural identity, the sustainability of production, and the transmission of knowledge were observed across diverse artisan trajectories. As coding advanced, thematic saturation was confirmed through the repeated identification of key categories: natural sericulture production, plant-dyed silk, innovation in natural dyeing, and intangible cultural heritage. These saturated themes were employed as the basis for an emerging theory of adaptive cultural continuity, in which the navigation between innovation and tradition was shown to sustain the vitality of intangible cultural heritage. Code saturation of the key informants is presented in Table 4, and the materials used in plant-based dye recipes for silk textile production are illustrated in Figures A1–A5.

Table 4. Participant confirmation of code saturation.

Code-Saturation Theme	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12	W13	W14	W15
Theme one															
A1. Sericulture plant	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
A2. Silkworm rearing house	*	*	*	*	*	*	*	*	_	*	*	*	*	*	*
A3. Cocoon processing unit	_	*	*	*	*	*	*	*	*	*	*	*	*	*	*
Theme two															
B1. Natural silk base	*	_	*	*	*	*	*	_	*	*	*	*	*	*	*
B2. Plant-based dyes	*	*	*	*	*	*	*	*	_	*	*	*	*	*	*
B3. Dyeing process	_	*	*	*	*	*	*	*	*	*	*	*	*	*	*

Table 4. *Cont.*

Code-Saturation Theme	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12	W13	W14	W15
Theme three															
C1. Revival natural dyeing practice	*		*	*	*	*	*	_	*	*	*	*	*	_	*
C2. Eco-friendly textile production	*	*	*	*	_	*	*	*	*	_	*	*	*	*	*
C3. Modern extraction techniques	*	*	*	*	*	*	_	*	*	*	*	*	*	*	*
C4. Innovative dyeing practice	*	*	*	*	*	*	*	*	_	*	*	*	_	*	*
Theme four															
D1. Weaving techniques and skills	*	*	*	*	*	*	*	_	*	*	*	*	*	*	*
D2. Design motifs and symbolism	*	*	*	*	*	*	*	*	*	*	*	_	*	*	*
D3. Adaptation and innovation	*	_	*	*	*	*	*	*	*	*	*	*	*	*	*
D4. Cultural and ritual significance	*	*	*	*	*	*	*	*	*	_	*	*	*	*	*

Note: (*) = participant confirmed code saturation; (–) = participant disconfirmed code saturation.

3.3. Findings for RQ1

In response to *RQ1*, this study was designed to examine how natural sericulture production is undertaken within silk textile practices in Maha Sarakham, northeast Thailand. The participants indicated that natural sericulture production was organised around the sericulture plant, the silkworm-rearing house, and the cocoon processing unit. With reference to the sericulture plant, supporting evidence for interview responses is provided by the following quotations:

> "We grow mulberry in our backyard. It is not only for silk but also part of our way of life—our grandmothers taught us everything."

> "The soil here makes the mulberry sweet and strong. That is why our silk differs from that of other provinces."

> "Silkworms are like family. They must be cared for every day, like children. If they are fed incorrectly, the silk is ruined."

> "Our silk begins with the land. If we do not care for the land, we cannot grow mulberry. It is all connected."

> "Sericulture is not only for money. It teaches patience, care, and respect for nature."

When responding to interview questions concerning the association between natural sericulture production and the silkworm-rearing house in silk textile production, the participants stated that the silkworm-rearing house was dependent on rearing trays or racks, a disinfection room, and mountages. The following quotations are provided to illustrate these key aspects of silkworm rearing:

> "We raise silkworms in the house our grandparents built. It is more than a job—it is part of who we are."

> "The rearing house must be clean and quiet. Silkworms are sensitive like babies; they feel everything."

> "I modified our old wooden house by adding mesh to control insects. It keeps the worms healthy and produces better silk."

> "The new silkworm house from the university project helped us reduce waste and improve cocoons."

Almost all the respondents addressed the semi-structured interview questions concerning the cocoon processing unit for natural sericulture production in Maha Sarakham, northeast Thailand. The cocoon processing unit was described as consisting of a cocoon drying or stifling chamber, a sorting and grading table, and a storage room. The following quotations are provided to illustrate respondents' perspectives on the cocoon processing unit:

"The boiling of cocoons must be done carefully—if the temperature is wrong, the thread will break. This is a skill you cannot learn only by watching; you have to feel it."

"Now we use a small reeling machine that saves time. But we still check the quality of every skein by hand."

"Before, we sold raw cocoons to middlemen. Now, with training from the local university, we process and dye the silk ourselves."

"Cocoon processing is more than work. It connects us to our ancestors and keeps our traditions alive."

"We started adding natural dyeing immediately after the reeling process. It brings more value and allows us to create our own brand."

3.4. Findings for RQ2

In response to *RQ2*, this study was designed to investigate how traditional knowledge of plant-based dyes is applied to safeguard natural silk textiles in northeast Thailand. The participants indicated that plant-based dyeing is associated with the natural silk base, the natural dyes, and the dyeing process (see Figures A1–A5). The plant-based dye processes of silk textile production are presented in Figures 1–3. The following quotations are provided to illustrate the participants' experiences of the natural silk base:



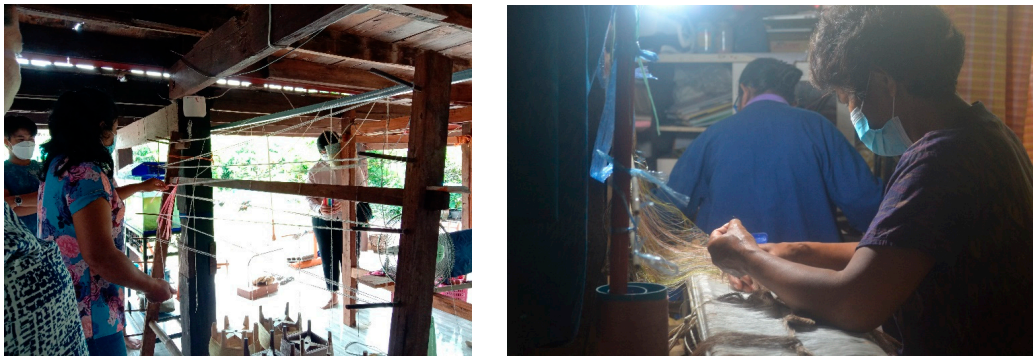
(**a**) (**b**)

Figure 1. Plant-based dye processes (1): (**a**) silk was immersed in dye solution; (**b**) washing silk yarn to remove impurities.



(**a**) (**b**)

Figure 2. Plant-based dye processes (2): (**a**) twisting silk yarn to remove excess moisture; (**b**) air-drying silk yarn.



(**a**) (**b**)

Figure 3. Weaving process preparation (2): (**a**) warp is threaded through heddles; (**b**) warp yarns are spliced to use loom.

> "We have raised mulberry silkworms for generations. The thread is soft and absorbs indigo dye beautifully—it is our signature."
>
> "Eri silk is peaceful—no killing of the worm. Many foreign buyers value it as cruelty-free and natural."
>
> "Tussar silk is harder to find here, but its golden colour is special. When dyed with sappanwood, it produces a deep, earthy red."
>
> "Muga silk is rare in Thailand, but I imported it from Assam. Its natural golden hue changes when dyed, creating a unique tone."

In response to the interview question concerning plant-based dyes in deep burgundy, violet or purple, and rust-orange, the participants' experiences with these dyes are described in the following quotations:

> "We boil sappanwood chips for a long time. If we add rusty nails or old iron tools, the red becomes deeper—almost like blood. We call it sii dang kao."
>
> "Indigo gives blue, but when mixed with mangosteen peel or old teak leaves, it turns into a rich violet. The older the leaves, the deeper the purple."
>
> "When we use jackfruit wood, it gives a golden colour. If we leave it longer or add tamarind bark, it turns orange—like the monk's robes."

In response to the interview question on the dyeing process, the components were described by the participants as scouring the silk, mordanting, dye extraction, dyeing, and rinsing or drying. The following quotations was are to reflect the participants' views:

> "Before we start, we wash the raw silk thoroughly in hot water with mild soap to remove impurities and sericin."
>
> "We soak the silk in a mordant bath, usually alum, to ensure the colour bonds well with the fibres."
>
> "The plant materials are boiled until the colour leaches into the water, creating a rich dye bath."
>
> "We immerse the silk in the dye bath and stir it gently to ensure the colour is absorbed evenly."
>
> "After dyeing, the silk is rinsed in clean water and hung in the shade to dry naturally."

3.5. Findings for RQ3

In response to *RQ3*, innovation in natural dyeing was concluded to be dependent on the revival of traditional dyeing practices, eco-friendly textile production, modern extraction techniques, and innovative dyeing methods. The use of locally sourced plant materials—such as indigo, jackfruit wood, sappanwood, mangosteen rind, and pomegranate peel—was identified by the participants as a means of reviving natural dyeing in silk textiles. Supporting evidence for this revival is provided by five participants in the following quotations:

> "Indigo is our identity. My grandmother taught me to ferment the dye with lime and rice wine. Today, we use the same method but measure the pH to make the colour last longer."

> "We used to throw away jackfruit branches, but now we boil them for golden dye. It is amazing that something so simple from our garden has become part of our product line."

> "Sappanwood gives a strong red. In the past, it was used for monks' robes. We still use it, but now combine it with iron water to produce deep purples for modern fashion."

> "My mother said mangosteen peel makes a good dye when mixed with alum. We never thought it could become part of eco-fashion—now foreigners want scarves made in this colour."

> "Pomegranate was once just fruit. Now we dry the peels and use them to dye silk in light browns and yellows. It is natural, organic, and connects us to older ways."

In response to the interview questions on eco-friendly textile production in silk textiles, the participants described its association with skill training in dyeing and intergenerational learning. The following quotations are provided to exemplify these experiences of eco-friendly textile production:

> "We organise dyeing workshops every year so the younger villagers can learn the traditional way—using local leaves, roots, and bark for dye."

> "My mother taught me to recognise which plants give red, yellow, or brown colours. I am now teaching my daughter in the same way."

> "We do not write it down—it is kept alive through watching, doing, and repeating."

> "When children join the dyeing, they learn more than colour—they learn our way of life."

In response to the interview questions, the modern extraction techniques were categorised by the participants as comprising drying and grinding, extraction methods, dyeing the silk, post-dye treatment, and finishing with quality control. The following quotations are provided to illustrate the participants' experiences with the modern extraction techniques:

> "We used to dry leaves only in the sun, but now we use a hot-air dryer to control moisture and prevent mould."

> "The microwave extractor makes the colour release faster and stronger, especially from hardwoods such as sappanwood."

> "We soak the silk longer in low-temperature baths. It helps the dye bond better and makes the colour last longer."

> "After dyeing, the silk is rinsed with natural soap and vinegar to help set the colour of the natural dyes."

> "Before selling, we check whether the silk fades in the sun or when washed. Now we use a checklist."

In response to the interview questions, innovative dyeing practices were reported by the participants as being integrated with colour layering techniques, modern design patterns, fashion collaborations, skill training in dyeing, and intergenerational learning. The following quotations are provided to illustrate these innovative approaches:

> "We no longer use only one colour per batch. Now we dip the silk in different natural dyes—blue first, then yellow—to create new tones such as green or olive that were not in the old patterns."

> "Young designers helped us adjust our motifs. The traditional diamond shape remains, but it is smaller and fits better on scarves or modern blouses."

> "A Bangkok fashion brand collaborated with our weavers. They used our hand-dyed silk for jackets on the runway. It is still our heritage, only in a new form."

> "Before, we only knew how to use indigo. After the workshop, we can now extract dye from eucalyptus and jackfruit wood as well. It gives us more options for customers."

> "Knowledge is exchanged across generations: traditional methods of identifying dye plants, such as Indigofera tinctoria, are passed down, while digital skills—such as marketing through social media—are shared in return."

3.6. Findings for RQ4

In response to *RQ4*, intangible cultural heritage was summarised as being associated with weaving techniques and skills, design motifs and symbolism, adaptation and innovation, cultural and ritual significance, local identity, and the regional economy (see Figures 4–6). The participants indicated that weaving techniques and skills encompassed twining and brocade methods, reed and heddle setup, colour blending through thread selection, finishing techniques, pattern memorisation, and the use of traditional wooden looms. This point was expressed by several participants in the following quotations:

> "To make the brocade shine, we pick the threads one by one with our fingers. It takes time, but the design comes alive."

> "Setting up the reed is the most important step. If a mistake is made there, the whole cloth becomes crooked."

> "We mix indigo and sappan-dyed threads to create a soft purple. It depends on how the colours interact in the light."

> "After weaving, we steam the cloth over herbal water. It softens the silk and enhances the natural colour."

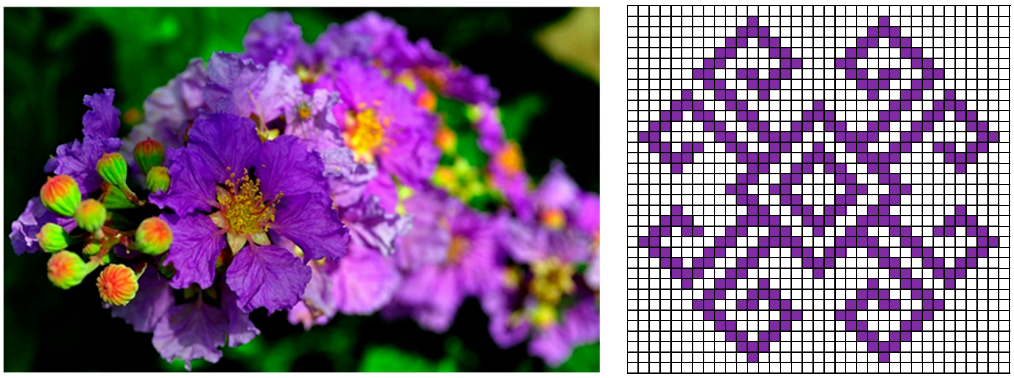
> "I do not use a pattern book. I remember it from my mother—each row is already in my head."

> "This loom belonged to my grandmother. It is made from local teak and still works better than the new ones."



(**a**) (**b**)

Figure 4. The procedure for threading the warp through the heddles (2): (**a**) the silk yarn is wound onto a spindle; (**b**) the warp yarns are adjusted before weaving.



(**a**) (**b**)

Figure 5. An innovative silk textile design pattern (2): (**a**) the flower of Lagerstroemia speciosa inspires the motif; (**b**) the Inthanin flower motif is expressed in textile design.



(**a**) (**b**)

Figure 6. The ikat weaving technique for the Inthanin flower motif (2): (**a**) Mudmee weaving depicts the Inthanin motif; (**b**) the ikat pattern conveys the symbolic meaning of the Inthanin flower.

In response to the in-depth interview, the significance of design motifs and symbolism was reiterated by the participants, with specific reference to the diamond motif, khid

patterns, the lotus flower, and cocoon patterns. The following quotations are provided to exemplify this theme:

> "The diamond shape is strong and balanced—our grandmothers believed it brings stability to the family."
>
> "This khid design is unique to our village. It is our identity. When people see it, they know it is from here."
>
> "The lotus is a sacred flower. We weave it to honour the temple and remind ourselves to live with a pure heart."
>
> "This cocoon pattern represents the life of the silkworm. It reminds us that from small things, beauty can grow."

In response to the interview questions, adaptation and innovation were outlined by the participants as involving the blending of traditional and modern motifs, the enhancement of natural dyes, the adoption of eco-conscious dyeing practices, the use of digital and social media marketing, and the development of community-based branding. The following quotations are provided to illustrate these processes:

> "We still use patterns my grandmother taught me, but I now combine them with modern geometric shapes. Younger customers prefer a simpler style."
>
> "Before, the colour faded quickly. With new boiling and filtering techniques, we achieve stronger shades that last longer, even after washing."
>
> "We no longer use chemical dye fixers. Everything now comes from the garden—alum, tamarind bark, even banana stems. It is safer for us and the river."
>
> "My daughter taught me how to post on Facebook. Now I can sell scarves to people in Bangkok without leaving the village."
>
> "We created a logo for our weaving group to show this is genuine Isan silk, made with natural dye. It helps build trust with customers."

In response to the interview questions, cultural and ritual significance was narrated by the participants as being expressed through ceremonial dress in Buddhist rituals, traditional wedding attire, festival and cultural identity displays, sacred symbolism in motifs, and the use of textiles in funerals and memorials. This cultural and ritual significance is evidenced in the following excerpts:

> "When we go to the temple, we wear our best silk—not to show off, but to show respect to the Buddha and our ancestors."
>
> "I wove my daughter's wedding skirt myself, using indigo and sappan dyes. It is our tradition. The patterns express who we are and where we come from."
>
> "Every year at the Bun Bang Fai Festival, we wear our village's colours and designs. People can tell where you are from simply by your textile."
>
> "The naga in our cloth protects the family. It is not just decoration—it is our belief."
>
> "For my father's funeral, we wrapped his body in silk dyed with tamarind bark. He said he wanted to go in peace, in something from the land."

In response to the interview questions, local identity and the regional economy were discussed by the participants in relation to cultural symbolism in patterns, integration into local dress, women's economic empowerment, and the growth of cultural and creative industries. The following quotations are provided to capture the tone of local identity and the regional economy in silk textiles:

> "We wear our silk when we go to the temple or during Songkran. It is not just clothing; it shows who we are."
>
> "We started a weaving group of fifteen women. With the profits, we built a small dyeing centre and trained the next generation."
>
> "We now sell to tourists and international markets. Our silk has moved from local to global, but it still holds our roots."

Four thematic groupings were identified through the analysis: natural sericulture production, plant-dyed silk, innovation in natural dyeing, and intangible cultural heritage. Across these domains, the artisans' practices were shaped by ecological resources, intergenerational knowledge transfer, and socio-economic drivers. BFPs were observed in shifts from traditional to natural dyes, transitions from subsistence to commercial production, and the adoption of digital marketing or cooperative models. EFPs were identified as the sustaining of cultural identity, the achievement of production sustainability, and the transmission of heritage skills. The emerging theory was positioned to characterise silk textile production in northeast Thailand as a dynamic, culturally embedded system in which innovation and tradition were interpreted as parallel, mutually reinforcing trajectories contributing to the adaptive continuity of intangible cultural heritage.

4. Discussion

4.1. Discussion of Findings

Natural sericulture production in Maha Sarakham was observed to persist through integrated ecological practices, intergenerational skill transmission, and adaptive infrastructure. Reliance was placed on locally cultivated mulberry, traditional silkworm-rearing houses, and community-based cocoon processing units, forming a socio-ecological system in which environmental stewardship and embodied knowledge were regarded as determinants of production quality. Alignment with the previous findings on the ecological embeddedness of sericulture in rural Southeast Asia was confirmed [1,9,11,14,16]. Through analysis with the TEM, the BFPs—such as transitions from traditional production to innovative natural silk practices—were interpreted as value-laden acts through which cultural identity was reinforced, intangible cultural heritage safeguarded, and sericulture production sustained. Natural sericulture was therefore characterised as a dynamic and adaptive practice, responsive to market and environmental pressures rather than as a static heritage activity [31].

The safeguarding of natural silk textiles was found to depend on the interaction of the silk base, botanical dye sources, and process knowledge [32]. Through the analysis with the TEM, the participants' expertise in colour extraction, mordanting, and dye sequencing was shown to secure both durability and symbolic depth in the textile outcomes. Consistency with the conclusions of Charungkiattikul and Joneurairatana [11] and Hossain et al. [33] was confirmed, indicating that plant-based dyeing was understood as both a material and cultural technology. The literature was extended by evidence that equifinality points—such as production sustainability and intergenerational knowledge transmission—were attained through divergent routes, including the revival of lost plant dyes and the integration of eco-friendly innovations. The traditional dyeing methods were therefore characterised as relevant when strategically adapted to contemporary environmental and market conditions.

Innovation in natural dyeing was found to be driven by four interconnected mechanisms: the revival of heritage techniques, eco-conscious production, modern extraction methods, and the fusion of traditional dyes with contemporary design requirements [34]. Local botanical resources, including indigo, sappanwood, and pomegranate peel, were mobilised for their chromatic qualities and appeal within eco-fashion networks. Align-

ment with prior scholarship on the synergy between sustainable innovation and cultural preservation was confirmed [35]. Through the analysis with the TEM, the BFPs—such as the adoption of digital marketing and collaboration with fashion designers—were shown to facilitate convergence towards equifinality outcomes, including economic resilience and heritage revitalisation. Innovation and tradition were therefore characterised as mutually reinforcing trajectories within heritage textile production systems rather than as opposing forces [36].

Weaving techniques, design motifs, and associated symbolism were found to constitute the cultural backbone of silk textile production in the region [37]. Skills in twining, brocade weaving, colour blending, and reed-heddle setup were identified as embedded within a wider matrix of cultural and ritual significance, including ceremonial dress, sacred symbolism, and expressions of local identity. Confirmation was provided for earlier claims that weaving functioned as a primary vehicle of intangible cultural heritage in Southeast Asian textile economies [12,14,20,23]. The discussion was extended through the analysis with the TEM, which showed that adaptation—such as the blending of traditional and modern motifs or the integration of eco-conscious dyeing—was interpreted as a strategic response to the dual imperatives of cultural preservation and market competitiveness. The equifinality points, including the reinforcement of local identity and the maintenance of ritual relevance, were demonstrated as attainable through varied configurations of innovation and tradition [25,34].

4.2. Practical Implications

The findings from to the four research questions were interpreted to indicate that sustainable innovation in plant-dyed silk textiles can be operationalised through ecological stewardship in sericulture, the safeguarding of traditional dyeing knowledge, the embedding of innovation pathways, and the reinforcement of intangible cultural heritage through weaving practices. These insights were found to be applicable within policy frameworks supporting artisan cooperatives, training programmes integrating heritage skills with modern extraction and design methods, and market strategies combining eco-conscious branding with cultural symbolism. Analysis with the TEM showed that BFPs—such as the adoption of digital marketing and eco-friendly techniques—could be strategically managed to achieve equifinality outcomes, including economic resilience, heritage revitalisation, and strengthened community identity. The evidence was interpreted as underscoring the enhancement of professional practice in heritage textile sectors by aligning tradition-preserving strategies with innovation-driven change, thereby securing both cultural continuity and competitive advantage in global markets.

4.3. Theoretical Contributions

The application of the TEM to plant-dyed silk textiles was found to extend our theoretical understanding of innovation and intangible cultural heritage as mutually reinforcing trajectories. Whereas the previous studies addressed heritage preservation [20] and craft innovation [23] separately, this research was shown to bridge them by demonstrating that BFPs—such as shifts from traditional to natural dyes and the adoption of modern marketing channels—functioned as cultural inflection points rather than operational adjustments. The analysis confirmed that equifinality outcomes, including cultural sustainability and economic resilience, could be attained through diverse adaptive pathways, thereby extending the TEM's applicability beyond psychology and education into heritage craft economies. A theoretical gap was addressed by integrating material processes, ecological adaptation, and symbolic meaning within a single analytical frame that linked tangible production with intangible cultural systems in a dynamic, process-oriented model.

The findings from the four research questions were found to refine the conceptualisation of intangible cultural heritage as a living, adaptive system, extending the argument of Chami et al. [9], with stronger empirical grounding in artisanal textile contexts. Weaving techniques, plant-based dyeing knowledge, and innovation practices were demonstrated to operate as interconnected domains shaped by ecological, socio-economic, and institutional forces. Intangible cultural heritage was therefore reconceptualised as an active site of negotiation between preservation and adaptation, challenging the static heritage models identified in earlier scholarship [38]. The research was shown to advance theory by demonstrating that the TEM operationalises this negotiation process and provides a replicable analytical framework for heritage-based industries under pressures of globalisation, environmental change, and market transformation.

4.4. Policy Initiatives

The findings from the four research questions were interpreted to indicate that policy interventions are strengthened when intangible cultural heritage safeguarding is embedded within sustainable production and market innovation strategies. Natural sericulture, plant-based dyeing, innovation pathways, and weaving traditions were shown to operate as interconnected domains shaping both cultural resilience and economic sustainability. These insights were found to be applicable to the existing frameworks, including UNESCO's 2003 Convention for the Safeguarding of Intangible Cultural Heritage and national rural development policies, ensuring that BFPs—such as the adoption of eco-friendly production methods and digital marketing—receive targeted support through funding, training, and cooperative schemes. The evidence derived from the TEM demonstrated that equifinality outcomes, including heritage revitalisation, identity reinforcement, and livelihood security, become attainable when policy mechanisms align preservation with innovation-driven economic strategies. This alignment was shown to enable policymakers to move beyond static heritage protection models towards adaptive, resilience-oriented frameworks that reflect the lived realities of artisan communities.

4.5. Potential Limitations

Limitations were encountered in the theory, the methodology, the findings, and the impact. The preservation of intangible cultural heritage in northeast Thailand was investigated through natural sericulture, plant-dyed silk, and dyeing innovations. The TEM was applied, and qualitative life history interviews were conducted with fifteen women weavers in Maha Sarakham Province. Although this method generated rich contextual insights, the generalisability of the findings beyond the study area was limited. Purposive sampling was also acknowledged to introduce potential selection bias by overrepresenting artisans already engaged in safeguarding or innovating heritage practices.

The thematic findings, though robust locally, were interpreted as reflecting the socio-economic and temporal conditions of the study period, leaving open the question of how policy or market shifts might alter bifurcation and equifinality patterns. The scale and structure of heritage textile markets, as well as the quantification of the economic viability of sustainable sericulture and plant-based dyeing, were not fully examined. The translation of the findings into policy and practice was found to depend on institutional will, funding, and community capacity, factors that lay beyond the empirical scope of this study. These constraints were interpreted as underscoring the need for future research to extend into international textile markets, integrate mixed method designs, and apply the TEM across heritage craft sectors to strengthen both theoretical robustness and practical relevance.

4.6. Future Research Paths

Future research was recommended to expand the geographic scope to include multiple silk-producing regions in Southeast Asia, enabling comparative analysis of bifurcation and equifinality across ecological, cultural, and economic contexts. Mixed method designs integrating ethnography, quantitative market analysis, and experimental dyeing trials were suggested to strengthen causal inference and to measure concrete outcomes of innovation–heritage integration. Heirloom textiles were preserved by artisans, yet detailed knowledge of the dyeing methods originally applied was often lacking. Historical practices of natural dyeing were reconstructed by the researchers, who frequently uncovered unexpected insights into traditional techniques. Longitudinal studies were recommended to trace artisan trajectories in order to capture the effects of shifting policies, global market pressures, and environmental change. The TEM was advised to be tested and adapted across other heritage craft sectors—such as natural fibre weaving and traditional pottery—to evaluate both transferability and theoretical robustness. Effective collaboration between scholars, policymakers, and artisan communities was suggested to co-produce actionable knowledge that aligns cultural preservation with innovation-led economic growth.

5. Conclusions

Natural sericulture production in Maha Sarakham was found to persist through ecological resource management, intergenerational skill transfer, and adaptive infrastructure, confirming its dual role as both an economic resource and a cultural asset (*RQ1*). The safeguarding of plant-based dyeing knowledge was shown to rely on the integration of material processes, botanical resources, and symbolic functions, thereby linking sustainability with heritage preservation (*RQ2*). Innovation in natural dyeing was observed to operate through the revival of the traditional techniques, the adoption of eco-conscious methods, the application of modern extraction processes, and the fusion of heritage dyes with contemporary market demands, generating reinforcing trajectories of tradition and innovation (*RQ3*). Weaving practices were identified as embodying intangible cultural heritage through technical skills, design motifs, and ritual symbolism, while adaptation strategies—such as motif blending and community branding—were shown to secure relevance within shifting socio-economic conditions (*RQ4*). Collectively, silk textile production in northeast Thailand was characterised as a dynamic, culturally embedded system in which artisans navigated BFPs to achieve equifinality in cultural identity, production sustainability, and heritage skill transmission.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in this study.

Data Availability Statement: Data is contained within the article.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Tannin-rich barks, roots, and leaves were employed in traditional recipes, boiled to release colourant compounds, and applied to silk through sequential immersion. In innovative adaptations, concentrated plant extracts, natural mordants such as alum, and controlled pH adjustments were incorporated to stabilise shades and improve fibre affinity. These trajectories were demonstrated to converge by sustaining heritage practices, while enabling novel applications that expanded the aesthetic and cultural value of silk. A comparison of traditional and innovative plant-based dye recipes in silk textile dyeing in Maha Sarakham Province, northeast Thailand, is presented in Table A1.

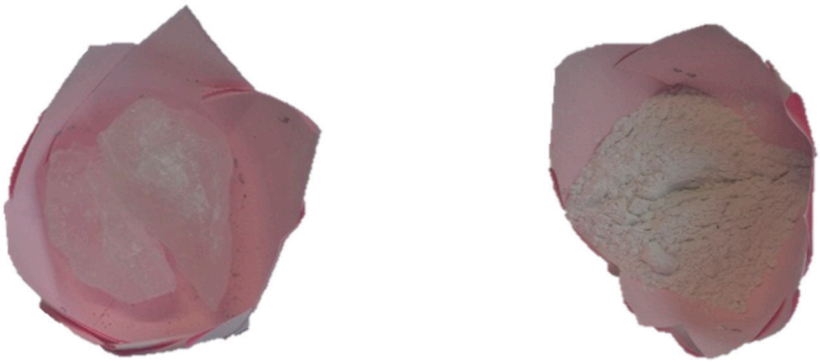
Table A1. Comparison of traditional and innovative plant-based dye recipes in silk textile dyeing.

Material Type	Traditional Practice	Innovative Practice	Process Description
Silk preparation	Local mulberry silk (Bombyx mori) was hand-reeled and degummed, with raw silk manually boiled to remove sericin.	Pre-treated eco-silk, including mechanically reeled, softened, or bleached fibre, was employed in innovative practice. Degumming was carried out industrially or with enzyme treatment.	Both methods were shown to be designed to produce clean silk fibre for optimal dye penetration, while fabric softness and dye absorption were enhanced through innovative techniques.
Dye plant collection	Fresh, seasonal dye plants such as Indigofera tinctoria, jackfruit wood, and mangosteen rind were collected from local forests or household gardens.	Powdered dye concentrates or standardised plant-extract kits were sourced for innovative practice, while some raw materials were grown in dye gardens or cultivated organically.	The traditional method was shown to depend on ecological cycles and local knowledge, whereas innovations were introduced to increase consistency and ensure year-round availability.
Silk fabric base	Locally handwoven silk, such as hand-reeled mulberry silk, was employed in traditional textile production.	Pre-treated, machine-reeled silk—such as eco-silk and soft-finish silk—was employed in innovative textile production.	Silk was harvested, degummed through boiling, and prepared for dyeing, while in innovative practice it was sometimes pre-scoured or chemically softened to enhance dye uptake.
Dye source (plant)	Raw plant materials such as whole leaves, bark, and roots from local sources, including Indigofera tinctoria and jackfruit wood, were employed in traditional dyeing practice.	Concentrated plant extracts or powdered natural dye kits were utilised in innovative dyeing practice.	Traditional dye sources were chopped and soaked or boiled, while innovative methods were introduced through enzyme- or ultrasound-assisted extraction to increase pigment yield and reduce waste.
Mordanting	Natural mordants such as alum, tamarind paste, or wood ash were employed in traditional dyeing practice.	Bio-based or synthetic eco-mordants—such as biodegradable tannins and metal-free mordants—were employed in innovative dyeing practice.	Mordants were used to fix dye to silk. Traditional methods were based on soaking in natural astringents, whereas innovative methods employed standardised, low-toxicity fixatives to secure consistent colourfastness.
Dye extraction method	Plant material was boiled in open pots with firewood, and extraction was carried out over long durations of two to four hours.	Enzyme-assisted, ultrasonic, or pressure-assisted extraction methods were employed to achieve shorter processing times.	Traditional methods were based on boiling plant material in large vats, while innovations were introduced through controlled heating and pH adjustments to improve pigment stability.
Dyeing method	Textiles were immersed in the dye bath, with repeated soaking undertaken to achieve depth of colour.	Layered dyeing techniques, controlled-temperature dyeing, resist methods, and digital pattern design were employed in innovative textile production.	Traditional immersion was associated with deep saturation but limited scope for patterning, while innovations were introduced through resist techniques such as tie-dye and clamp-dye, digital motif mapping, and precise layering of multiple dyes.
Fixing and drying	Textiles were sun-dried after dyeing, and fixatives were applied post-dye.	Controlled drying with UV protection and post-dye coating with eco-fixative sprays were employed in innovative finishing processes.	Traditional sun-drying was associated with uneven colouration, while modern methods were introduced through drying chambers and aftercare treatments to secure colourfastness.
Post-dye treatment	Textiles were sometimes treated with rice starch to add stiffness or re-dyed to deepen colour, and each piece was manually inspected.	Natural fixatives or post-treatment sprays were applied to improve durability, enhance sheen, and support eco-certification.	Post-processing was employed to preserve dye and fabric quality, while in modern finishing attention was also directed to softness, washability, and export compliance.
Weaving and finishing	Traditional wooden looms were employed, with patterns committed to memory and executed manually.	CAD-assisted loom design and the integration of dye patterns into weave planning were employed in innovative textile production.	Traditional looms were shown to require skilled, memory-based pattern creation, while innovations were enabled through digital pattern simulation, which allowed complex colour–weave integration.
Design motifs	Examples of region-specific symbols were given as the naga, the diamond, and the lotus.	Fusion motifs blending traditional symbols with contemporary design were employed in innovative textile production.	Traditional motifs were recognised as carrying cultural significance, while new designs were adapted from these forms for modern fashion and export markets, often in collaboration with designers.

Appendix B

Alum and calcium oxide were employed as mordants to prepare silk fibres for dye absorption. Natural colourants were obtained from Indigofera tinctoria, lac with tamarind

paste, iron rust with Artocarpus lacucha, and extracted Wrightia arborea. Lac dye was extracted by boiling in water, and impurities were removed through filtration to yield a clarified solution. These materials were demonstrated to illustrate the integration of mineral mordants and botanical sources in sustaining both traditional knowledge and innovative textile applications (see Figures A1–A5).



(**a**) (**b**)

Figure A1. Raw materials used in plant-based dye recipes (1): (**a**) alum acts as natural mordant; (**b**) calcium oxide prepares fibres for dye absorption.



(**a**) (**b**)

Figure A2. Raw materials used in plant-based dye recipes (1): (**a**) Indigofera tinctoria provides blue dye source; (**b**) lac supplies natural red colourant.



(**a**) (**b**)

Figure A3. Raw materials used in plant-based dye recipes (2): (**a**) tamarind paste serves as natural mordant; (**b**) iron rust provides mineral dye source.



(**a**) (**b**)

Figure A4. Raw materials used in plant-based dye recipes (3): (**a**) Artocarpus lacucha provides natural dye source; (**b**) extracted Wrightia arborea supplies plant-based colourant.



(**a**) (**b**)

Figure A5. Raw materials used in plant-based dye recipes (4): (**a**) boiling in water extracts natural dye from lac; (**b**) filtration removes impurities and residual solids from lac extract.

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