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Algorithmic Sustainability: Developing A Mathematical Model for Silk Credits Based On Carbon Avoidance And Product Longevity In Artisanal Textiles

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ABSTRACT: The global textile industry faces mounting pressure to substantiate its environmental claims, yet artisanal silk producers despite their comparatively low-carbon, non-industrialized production methods, still remain largely excluded from formal carbon finance mechanisms. This gap is compounded by two unresolved methodological problems when voluntary carbon credit markets have been shown to systematically overstate achieved emission reductions due to non-conservative baseline-setting, and product longevity, despite being identified as a major lever for reducing the environmental footprint of textiles, is rarely operationalized as a quantifiable variable within existing crediting frameworks. This paper develops a basic mathematical model termed the Silk Credit (SC) that integrates two components, carbon avoidance (CA) and a longevity factor (LF), combined through a hybrid Entropy-AHP weighting scheme ($SC = w_1 \times CA + w_2 \times LF$), grounded in Triple Bottom Line theory and composite-indicator construction methods. A survey-based research design is proposed to operationalize the model across three artisanal silk-weaving villages in Hanoi (Van Phuc, La Khe, and Phung Xa) collecting primary activity data from producing households and willingness-to-pay data from consumers, with reliability assessed via Cronbach's alpha and hypothesis testing conducted through multiple regression and PLS-SEM. An application of the model demonstrates its operational feasibility, showing differentiated SC scores across villages and a statistically plausible positive relationship between the SC index, consumer willingness to pay, and trust in algorithmic verification. The study contributes a transparent, survey-grounded alternative to conventional carbon crediting approaches and offers a replicable framework for valuing environmental and durability performance in artisanal, non-industrialized textile production. Theoretical, policy, and practical implications are discussed, along with the study's limitations and directions for empirical validation.

KEYWORDS: Artisanal textiles; carbon avoidance; composite sustainability index; product longevity; silk credits.

I. INTRODUCTION

The global textile and apparel industry is under increasing pressure to demonstrate measurable environmental responsibility in response to climate change and the transition toward a circular economy. The global fashion industry was estimated to generate approximately 2.1 billion tonnes of greenhouse-gas (GHG) emissions in 2018, equivalent to around 4% of global emissions, with approximately 70% originating from upstream activities such as raw-material production, preparation, and processing (Global Fashion Agenda & McKinsey & Company, 2020). Within this context, the environmental performance of natural fibres cannot be assumed to be inherently low-impact. Silk is a particularly relevant case because its production involves multiple resource-intensive stages, including mulberry cultivation, silkworm rearing, cocoon production, silk reeling, dyeing, and finishing. An life cycle assessment (LCA) of Indian silk by Astudillo et al. (2014) found that, on a mass basis, silk production generated higher environmental impacts than those reported for several other natural fibres with cocoon production particularly fertilization representing a major source of environmental burden. More recent factory-level research in China has further demonstrated substantial variation in the carbon footprint of raw silk, ranging from 2.41 to 28.56 kg CO_2e per kg of raw silk across five silk-reeling factories, with energy consumption accounting for 89.1–96.5% of total emissions (Dai et al., 2025). These findings indicate that the environmental performance of silk depends strongly on production practices, energy systems, and geographical context rather than simply on its classification as a natural fibre. This issue is particularly relevant to Vietnam, where textiles and garments are among the country's major export-oriented manufacturing industries. According to the General Statistics Office of Vietnam, textile and garment exports reached approximately US$37 billion in 2024, increasing by 11.2% compared with 2023

and remaining among the country's leading export groups (GSO, 2025). At the same time, Vietnam has a large and culturally significant network of traditional craft villages. Government sources report more than 5,400 craft villages nationwide, while the traditional handicraft sector provides employment for approximately 1.5–1.58 million workers (Government News, 2022; Vietnam News, 2023). Silk weaving forms part of this traditional production system, with Vạn Phúc in Hanoi representing one of the country's best-known silk villages. The coexistence of a large industrial textile sector and an extensive artisanal craft economy provides Vietnam with a particularly relevant setting for examining whether localized, small-scale textile production can generate measurable environmental benefits relative to industrial alternatives.

Traditional artisanal silk production is often characterized by small-scale operations, localized supply chains, labour-intensive processes, limited mechanization, and strong connections to cultural heritage. These characteristics may reduce certain forms of energy use and transportation compared with highly centralized industrial production, but an environmental advantage cannot be assumed simply because a product is handmade or traditional. Differences in fuel sources, electricity consumption, cocoon processing, reeling technologies, dyeing practices, transportation, wastewater management, and product use can substantially affect life-cycle impacts. Existing LCA research illustrates this complexity. Yang et al. (2020), for example, found that silk reeling had important impacts on water quantity and eutrophication, while dyeing and finishing contributed substantially to water acidification and ecotoxicity. Similarly, recent research on raw-silk production has identified cocoon drying and silk reeling as major carbon hotspots depending on the energy structure of individual factories (Dai et al., 2025). Consequently, a meaningful comparison between artisanal and industrial silk requires a consistent functional unit and system boundary covering the relevant stages of the product life cycle rather than relying on assumptions about production scale or production technology.

Product longevity introduces an additional dimension that is particularly relevant to this comparison. From a life-cycle perspective, the environmental burden of a textile product depends not only on how it is produced but also on how long it remains in active use. The European Environment Agency identifies longevity, durability, repairability, reuse, and recycling as key pathways for reducing the environmental impacts of textiles, and emphasizes that life-extending strategies should be prioritized alongside material recycling (EEA, 2022). A review by Lujan-Ornelas et al. (2020) similarly highlights the importance of extending textile product lifetimes within a life-cycle-thinking framework. For artisanal silk, longevity may be particularly relevant because products can embody craftsmanship, cultural meaning, perceived quality, and emotional attachment in addition to their physical material properties. If a durable artisanal silk product remains functional and valued for a longer period than a comparable product, its potential environmental benefit may extend beyond lower production-stage emissions to include the avoidance of replacement products. However, this relationship has rarely been operationalized as a quantitative parameter within carbon accounting for artisanal silk. At the same time, converting such environmental benefits into a tradable carbon value raises a separate methodological challenge. The credibility of voluntary carbon markets has increasingly been questioned because of uncertainties surrounding additionality, baseline construction, leakage, and the accuracy of emission-reduction estimates. In a systematic assessment of 14 empirical studies covering 2,346 carbon-crediting projects, Probst et al. (2024) estimated that less than 16% of the credits issued in the investigated projects corresponded to actual emission reductions, although the results varied substantially across project types. The authors identified methodological and incentive-related problems, including unrealistic baselines and non-conservative assumptions, as important contributors to the gap between credited and achieved emission reductions. This evidence suggests that a new crediting mechanism for artisanal textiles should not simply assign credits to products that appear environmentally preferable. Instead, it would require a transparent counterfactual baseline, explicit treatment of additionality and leakage, conservative uncertainty adjustments, clearly defined system boundaries, and safeguards against double counting. In this context, the concept of a “Silk Credit” should be understood initially as a proposed measurement and valuation framework rather than as an assumption that artisanal silk automatically qualifies for carbon credits.

Against this background, three interrelated research gaps emerge. First, although existing studies have examined the environmental impacts of silk production, the literature reviewed in this study reveals limited integration of carbon avoidance and product longevity within a single quantitative framework for artisanal silk. Second, there is a need for a transparent and verifiable approach that can translate measurable environmental performance into sustainability linked value while addressing methodological concerns associated with baseline setting, additionality, and over crediting in existing carbon crediting systems. Third, despite the important economic and cultural role of Vietnam’s craft villages, empirical evidence at the product level concerning the environmental performance and longevity of Vietnamese artisanal silk remains limited. In response to these gaps, this study proposes a basic mathematical framework for a Silk Credit (SC) index that combines two core components: (i) quantitatively estimated carbon avoidance relative to a clearly defined industrial baseline, and (ii) a longevity factor reflecting the durability and useful lifetime of the artisanal product. Primary quantitative data are collected from production households, artisans, producers, consumers, and relevant stakeholders in Vietnamese silk producing communities to assess production

inputs, energy consumption, emissions, product longevity, repair and reuse practices, and other relevant variables. Rather than assuming that artisanal silk is inherently more sustainable than industrial silk, the study seeks to identify the empirical conditions under which potential environmental advantages can be measured, conservatively quantified, and potentially translated into credible sustainability linked economic value. In doing so, the study contributes a quantitative framework that connects life cycle assessment, carbon accounting, product longevity, sustainable production, and the economic valorization of traditional textile craftsmanship. The study is organized into five sections: (1) Introduction; (2) Literature review and equation model; (3) Methodology; (4) Results and discussion; and (5) Conclusion and policy implications.

II. LITERATURE REVIEW AND EQUATION MODEL

Sustainable development and the Three-Pillar model

The theoretical foundation of this study is rooted in the Triple Bottom Line (TBL) framework of sustainable development proposed by Elkington (1997). Under this framework, the performance of an organization or production system should be evaluated simultaneously across three dimensions: economic (profit), social (people), and environmental (planet), rather than being assessed solely on the basis of conventional financial indicators. The TBL framework provides a theoretical basis for explaining why a handcrafted silk product, which is closely associated with the livelihoods of craft village communities through the social dimension and with production processes characterized by relatively low dependence on fossil fuel energy through the environmental dimension, can be conceptualized as a unit embodying integrated sustainability value. This provides a foundation for translating such value into an economic measurement unit such as a carbon credit. Accordingly, this study adopts the underlying logic of the TBL framework to conceptualize the "silk credit" as a mechanism for quantifying two of the three aforementioned dimensions, namely the environmental dimension through avoided carbon emissions and a component of the economic and social dimensions through product durability and service life, which reflect the quality of craftsmanship and the cultural value embodied in artisanship.

Carbon footprint and life cycle assessment in the silk industry

Life Cycle Assessment (LCA), standardized under ISO 14040 and ISO 14044 and complemented by the product carbon footprint standard ISO 14067, has become one of the most widely applied methodological approaches for quantifying the environmental impacts of textile products in recent academic research (International Organization for Standardization, 2006, 2018). Within the silk industry, LCA studies indicate that water and carbon footprints are concentrated primarily in silk reeling, dyeing, and finishing processes, whereas mulberry cultivation and silkworm production may contribute to a certain degree of carbon sequestration through photosynthesis (Yang et al., 2020). Chen et al. (2020) examined the environmental and water resource impacts associated with silk garment production and demonstrated that wet processing stages, including dyeing, washing, and sizing, constitute the major hotspots in terms of water consumption. From a gate to gate carbon footprint perspective, quantitative studies applying ISO 14067 to silk reeling facilities in China have further demonstrated that the type of energy source used, including coal, grid electricity, and renewable energy, together with geographical location, represents two major determinants of emission intensity for raw silk production.

Ricciardi et al. (2020) in their assessment of the environmental sustainability implications of increasing silk demand in India, emphasized the importance of production scale. Household based and non industrialized sericulture systems tend to exhibit substantially lower emission intensity per unit of output than highly industrialized silkworm farming systems. Similarly, Altman & Farrell (2022) argued that sericulture can inherently be considered a sustainable agricultural activity when operated under traditional production conditions, owing to its compatibility with diversified agricultural ecosystems and its relatively low reliance on chemical inputs. These findings provide important empirical support for the central hypothesis of this study, namely that handcrafted silk, owing to its small scale and non industrialized production characteristics, may achieve positive carbon avoidance when compared with a baseline scenario represented by an equivalent industrial silk production process. More broadly, within the textile sector, Peters et al. (2015) systematically reviewed methodologies for calculating carbon footprints across different types of textile fibers. Yasin et al. (2018) further demonstrated that optimization of the end of life stage can substantially alter the results of textile LCA studies. These findings reinforce the argument that a carbon quantification model for textile products should not disregard the use and disposal stages of the product life cycle. This consideration provides the direct conceptual basis for incorporating product durability and service life as variables within the proposed silk credit model.

Carbon credit mechanisms and carbon avoidance

From a methodological perspective, the World Bank guidance on establishing domestic carbon crediting mechanisms (World Bank, 2021) emphasizes that an avoidance carbon credit is valid only when the activity demonstrates additionality, meaning that

the corresponding emission reduction would not have occurred in the absence of the crediting mechanism. The quantity of avoided emissions is determined as the difference between baseline emissions and actual project emissions, after accounting for emission leakage. The fundamental formulation, expressed as carbon credits equal baseline emissions minus actual emissions minus leakage, constitutes the mathematical starting point for avoidance crediting models, including the silk credit model proposed in this study. However, the most recent comprehensive assessments of the actual effectiveness of carbon crediting projects reveal significant methodological concerns. Based on an analysis of 14 empirical studies covering 2,346 projects and nearly one billion tonnes of CO2 equivalent that had been credited, the average actual emission reduction was found to be less than 16% of the volume of credits issued, with substantial variation across different project types (Probst et al., 2024). The principal causes have been associated with the establishment of baselines based not on direct observations but on counterfactual estimations, as well as with incentives for project developers to maximize the volume of credits issued. This finding has direct methodological implications for the present study. The silk credit model should therefore adopt a conservative approach to baseline establishment and prioritize primary data collected directly through field surveys in craft villages over default emission factors. Such an approach is expected to reduce the risk of over crediting, which constitutes one of the fundamental quality criteria emphasized in contemporary carbon credit quality assessment frameworks.

With respect to transparency and verification, recent studies suggest that blockchain technology and algorithmic verification mechanisms may provide potential solutions to the aforementioned limitations. Agrawal et al. (2021) proposed a blockchain based framework for traceability within textile supply chains through an algorithmically verified mass balance mechanism. Under this mechanism, each material transaction, such as the transfer of organic cotton, is reconciled with the actual quantity of material held by the respective transacting party. Centobelli et al. (2022) further concluded that blockchain technology can contribute to enhancing trust, traceability, and transparency within circular supply chains through its decentralized, verifiable, and tamper resistant distributed ledger architecture. These characteristics suggest the potential application of an algorithmic verification layer to the proposed silk credit model. Under such a framework, primary survey data concerning production volume, energy consumption, and product durability at the level of individual artisan households could be encoded, aggregated, and processed according to a standardized credit calculation formula that can be independently verified. This approach would reduce reliance on subjective estimations by project developers, which has been identified as a limitation in a number of conventional carbon crediting mechanisms.

Product longevity as an environmental variable

A distinct yet closely related stream of research focuses on the relationship between product durability and environmental impacts in the fashion industry. Research conducted by WRAP (Waste and Resources Action Programme) in the United Kingdom indicates that extending the average active lifetime of a garment by nine months can reduce its associated carbon, water, and waste footprints by approximately 20%. Claxton & Kent (2020), through a qualitative study involving stakeholders across the British fashion industry, demonstrated that decisions made during the new product development stage play a critical role in determining the potential longevity of garments. The authors also clearly distinguished between two concepts that are frequently conflated: technical durability, which refers to the inherent properties of materials and product construction, and actual use longevity, which refers to the period during which a product is actually used and is additionally influenced by consumer behavior, repairability, and the emotional value attached to the product.

Within the context of handcrafted textiles, durability is generally regarded as an inherent advantage. Studies of the handloom textile sector in India indicate that handloom products, owing to their limited production volumes, sophisticated craftsmanship, and relatively low degree of standardization, tend to be designed for extended use, thereby reducing adverse environmental impacts while generating positive social outcomes for craft village communities. Bhalla et al. (2018), through a comprehensive life cycle assessment of the Khadi Handloom industry in rural India, proposed an integrated rural development model based on LCA. Their findings demonstrated the feasibility of integrating product life cycle data with livelihood development objectives for artisan communities. This represents an important methodological precedent for the field survey approach proposed in the present study for silk weaving craft villages.

The intersection between the two research streams concerning carbon avoidance and product durability, constitutes the central theoretical gap that this study seeks to address. Up to now, LCA models and carbon crediting mechanisms have largely treated carbon avoidance at the production stage as an independent variable, separate from the actual use lifetime of a product after it reaches the consumer. However, as discussed above, actual product longevity is a critical determinant of the amount of emissions avoided per unit of product use time. This mathematical logic constitutes a key mechanism that will be operationalized in the research model presented in this section.

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Composite index quantification and weighting for the silk credit model

From the perspective of mathematical model development, this study builds upon the composite indicator approach, which has been extensively developed and applied in the field of sustainable development assessment. Zhou et al. (2007) proposed a mathematical programming approach for constructing composite indicators without requiring the a priori specification of subjective weights, thereby addressing a common limitation associated with fixed weighting methods. In a subsequent study, Zhou et al. (2010) extended this approach through a multiplicative optimization approach, in which the weights of individual component indicators are determined through a series of data envelopment analysis models that can be transformed into equivalent linear programming problems. Krajnc et al. (2007) applied a fuzzy logic model to benchmark performance in the sugar industry based on available best practices, demonstrating the applicability of flexible mathematical methods to the treatment of uncertain data. Such uncertainty is particularly relevant to survey data collected from informal production systems such as traditional craft villages.

In addition, the Analytic Hierarchy Process (AHP) developed by Saaty (1980) remains one of the most widely used subjective weighting techniques in multicriteria decision making models related to sustainable development. The method relies on pairwise comparisons using the Saaty 1 to 9 scale and is valued for its simplicity, scalability, and capacity to assess the consistency of expert judgments through the consistency ratio. To address the inherent subjectivity of AHP, Chen (2020) proposed an integrated Entropy AHP and TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) model, in which objective weights derived from the Entropy method are combined with subjective weights obtained through AHP to reduce bias arising from purely subjective assessments. This combined objective and subjective weighting approach is considered appropriate for the proposed silk credit model, in which the weights assigned to the carbon avoidance component and the durability and longevity component should be determined based on both objective quantitative survey data, such as energy consumption and measured average product lifetime, and expert assessments concerning policy priorities.

For the silk credit model to have practical applicability, it is necessary to consider the potential conversion of the credit into market value. Mostafa (2016), using the contingent valuation method among Egyptian consumers, demonstrated that willingness to pay for carbon labeled products is significantly influenced by consumers' socioeconomic characteristics. This finding suggests that the market value of a carbon credit associated with a consumer product should not necessarily be treated as a constant but may vary according to market segments and demographic characteristics. Other large scale market surveys have similarly reported that although a substantial proportion of consumers worldwide express a willingness to pay a price premium for sustainable products, a considerable gap remains between consumers' stated willingness to pay and the actual price premiums applied by businesses to sustainable products. One contributing factor is consumers' difficulty in distinguishing the actual level of sustainability among products when a reliable and comprehensible quantitative assessment system is absent. This finding further supports the need for a standardized and readily interpretable silk credit indicator that can provide a basis for consumers and purchasers to make objective comparisons among different handcrafted textile products.

Research gap and proposed equation model

A synthesis of the aforementioned research streams reveals three specific research gaps. Firstly, existing LCA studies on silk primarily focus on quantifying emissions at the production stage but rarely establish a direct connection with field survey data from informal handcrafted production systems. Secondly, carbon crediting methodologies have revealed substantial limitations concerning conservativeness and verifiability, creating a need for a more transparent and algorithmically implementable alternative model. Thirdly, although product durability and longevity have been demonstrated to exert a substantial influence on environmental footprints, these variables have rarely been explicitly and quantitatively integrated into a carbon credit model specifically designed for handcrafted textile products. On this basis, the study proposes a conceptual model consisting of two principal components and an algorithmic weighting mechanism, expressed through the following general function:

$SC = f(CA, LF) = w_1 \times CA + w_2 \times LF$

where SC (Silk Credit) represents the silk credit index of an individual product unit or production household; CA (Carbon Avoidance) represents the standardized quantity of avoided carbon emissions, calculated as the difference between emissions under an equivalent industrial baseline scenario and the actual emissions measured through field surveys in craft villages, after accounting for leakage risks, following the quantitative logic of World Bank (2021) and Probst et al. (2024); LF (Longevity Factor) represents the product longevity and durability factor, constructed based on survey data concerning average active use lifetime, repairability, and product reuse rates, following the measurement logic of Claxton & Kent (2020) and the data reported by WRAP; and w_1 and w_2 represent the component weights determined through a combined objective Entropy method and subjective AHP approach, following the approaches of Chen (2020) and Zhou et al. (2010). The weighting scheme ensures that

the sum of the component weights equals 1 and reflects both empirical evidence and expert assessments of the relative priority assigned to the two dimensions of environmental performance and product longevity.

The proposed model will be empirically examined through four general research hypotheses. H1 proposes that the degree of non industrialization of the production process, reflected in the proportion of manual labor and fossil fuel energy consumption, is positively associated with the CA component value. H2 proposes that product use longevity and repairability are positively associated with the LF component value. H3 proposes that the composite Silk Credit index (SC) is positively associated with consumers' willingness to pay, following the underlying logic proposed by Mostafa (2016). H4 proposes that the implementation of an algorithmic and blockchain based data verification layer increases the perceived reliability and acceptance of the SC index among both producers and end consumers, following the approaches proposed by Agrawal et al. (2021) and Centobelli et al. (2022). Data for testing these hypotheses will be collected through quantitative surveys involving production households, artisans, and a sample of consumers with an interest in handcrafted silk textile products.

III. METHODOLOGY

Research design

This study adopts an exploratory sequential mixed methods design implemented through two consecutive phases. Phase 1, comprising the qualitative instrument development stage, employs expert interviews and pairwise comparisons using the Analytic Hierarchy Process (AHP) to determine the measurement structure and preliminary weights for the two components of the proposed model, namely Carbon Avoidance (CA) and the Longevity and Durability Factor (LF) (Saaty, 1980). Phase 2, comprising the quantitative large scale survey stage, employs structured questionnaires targeting two groups of respondents: (i) artisanal silk production households and silk artisans, in order to collect activity data for calculating the CA component and product durability data for calculating the LF component; and (ii) consumers interested in silk products, in order to test hypotheses H3 and H4 concerning the relationship between the Silk Credit index (SC), willingness to pay, and perceived trust in the algorithmic verification mechanism. A cross sectional design is adopted due to the time and resource constraints of the study and because it is appropriate for the objective of developing and conducting a preliminary empirical validation of a new mathematical model rather than examining changes over time.

Sampling methods and data collection

The primary unit of analysis is the artisanal silk production household or workshop, which is conceptualized as the unit responsible for producing a specific product batch for which the Silk Credit index is calculated. The geographical scope of the survey focuses on representative traditional silk weaving craft villages in Vietnam, namely Van Phuc Silk Village in Ha Dong, Hanoi; La Khe Silk Village in Ha Dong; Phung Xa Silk Village in My Duc. These locations continue to maintain traditional handcrafted production processes, have long histories of craft development, and exhibit substantial variation in production scale. Such characteristics provide favorable conditions for comparing activity data across production establishments. The second unit of analysis is the end consumer. The consumer sample is restricted to individuals who have previously purchased or intend to purchase silk or handcrafted textile products, thereby ensuring the relevance of the collected data to variables measuring willingness to pay and perceptions of sustainable labels and credit mechanisms. Because the population of artisanal silk production households in each craft village is finite and can be estimated using statistical information provided by local authorities and craft village associations, the minimum sample size for the producer group is determined using the Yamane (1967) formula $n = N / (1 + Ne^2)$, where n represents the required sample size, N represents the population size, defined as the number of active artisanal silk production households in the surveyed craft villages, and e represents the allowable sampling error, which is set at 5%, corresponding to a 95% confidence level.

Proportionate stratified sampling is employed, with craft village and production scale serving as the stratification criteria. Production scale is classified into individual households, cooperative production groups, and small enterprises. This approach is intended to ensure adequate representation across different production scales, which may directly influence the value of the Carbon Avoidance component (CA), consistent with the findings of Ricciardi et al., (2020) concerning the relationship between production scale and emission intensity in the silk industry.

For the experts participating in the AHP pairwise comparison process during Phase 1, purposive sampling is employed. A minimum of 8 to 12 experts is selected from three groups: (i) researchers specializing in LCA and carbon footprints in the textile sector, (ii) representatives of artisans and craft village cooperatives, and (iii) experts in climate finance and carbon credit markets. This composition is intended to ensure a balance between technical and practical perspectives when determining the weights w_1 and w_2.

For the consumer group, the minimum sample size is also determined using the Yamane (1967) formula under an infinite or unspecified population assumption, resulting in an approximate sample size of 385 respondents at a 95% confidence level and a 5% margin of error. This is combined with controlled convenience sampling using quota sampling based on basic demographic characteristics.

Data from production households are collected through face to face structured interviews combined with direct observation at production workshops. This approach enables the researchers to cross check the consistency between information reported by respondents and directly observable evidence, such as electricity bills and records of input materials, thereby reducing potential reporting bias. Consumer data are collected through a combination of online surveys and direct surveys conducted at retail locations selling silk and handicraft products. Data for the AHP pairwise comparison process are collected through semi structured expert interviews. Each expert is asked to assess the relative importance of the CA and LF components, as well as the relative importance of subcriteria within each component, using the 1 to 9 Saaty scale (Saaty, 1980). The consistency ratio (CR) is subsequently calculated for each pairwise comparison matrix. Assessments producing a CR greater than 0.1 are returned to the respective experts for review and adjustment in order to improve the logical consistency of the judgments.

Measures and questionnaire design

The questionnaire for production households is structured into four sections. Section A collects general information about the production establishment, including workforce size, the proportion of production stages performed manually compared with those performed using machinery, and years of operation. Section B collects activity data required to calculate the CA component, including electricity, coal, firewood, and water consumption at each production stage, namely silkworm cultivation, silk reeling, dyeing, weaving, and finishing. The structure of this section is developed based on the system boundaries and parameter inventory specified under ISO 14067:2018 for product carbon footprints (International Organization for Standardization, 2018) and the gate to gate LCA analytical framework applied in previous studies of silk reeling facilities in China. The activity data are subsequently multiplied by corresponding emission factors to estimate the actual emissions of each production establishment. These estimates are then compared with an equivalent industrial baseline established using secondary data from existing industrial silk LCA studies, following the conservative baseline principle recommended by World Bank (2021) and Probst et al. (2024). Section C measures the LF component through variables concerning estimated average product use lifetime, repairability and reusability, and the proportion of defective products and discarded products. These measures are developed based on the conceptual framework of durability and longevity proposed by Claxton & Kent (2020) and benchmarking data reported by WRAP. Section D employs a five point Likert scale to measure artisans' perceptions of the potential value of a silk credit mechanism.

The consumer questionnaire consists of three sections. The first section employs a five point Likert scale to measure perceptions and attitudes toward sustainable textile products. The scale is developed based on previously validated measures used in studies of sustainable consumer behavior. The second section uses contingent valuation questions based on the methodology of Mitchell & Carson (1989) to estimate consumers' willingness to pay a premium for silk products carrying the SC credit index, with reference to the measurement approach applied by Mostafa (2016) to carbon labeled products. The third section measures the level of trust in an algorithmic and blockchain based data verification mechanism and is used to test hypothesis H4. All questionnaires undergo a pilot test involving a small sample of approximately 20 respondents from each target group before the formal data collection process. The pilot test is conducted to refine wording, assess response time, and identify potentially ambiguous or confusing questions.

Data analysis

Before the main statistical analysis, the internal reliability of the multidimensional Likert scales, including Section D of the producer questionnaire and the attitude and trust scales in the consumer questionnaire, is assessed using Cronbach's Alpha (Cronbach, 1951), with a minimum acceptable threshold of 0.7. The CA and LF components are normalized to a common measurement scale using min max normalization prior to aggregation, following the composite indicator construction approach proposed by Zhou et al. (2007). The weights w_1 for CA and w_2 for LF in the equation $SC = w_1 \times CA + w_2 \times LF$ are determined using a combination of two sources. The first source consists of subjective weights derived from the AHP pairwise comparisons conducted with experts (Saaty, 1980). The second source consists of objective weights calculated using the Entropy method based on the degree of dispersion observed in the empirical survey data, following the integrated Entropy AHP approach of Chen (2020) and the multiplicative optimization approach to composite indicator construction proposed by Zhou et al. (2010).

The combination of these two weighting sources is intended to simultaneously reduce the limitations associated with the purely subjective nature of AHP and the lack of explicit policy orientation that may characterize an Entropy based weighting

approach when applied independently. To test hypotheses H1 and H2, concerning the relationship between the degree of non industrialization and CA and the relationship between product longevity and repairability and LF, respectively, the study employs multiple linear regression analysis using data collected from production households. For hypotheses H3 and H4, concerning the relationship between the SC index and willingness to pay and between the SC index and trust in the algorithmic verification mechanism, respectively, the study employs Partial Least Squares Structural Equation Modeling (PLS SEM). This approach is appropriate because the proposed model incorporates latent constructs that are indirectly measured through multiple observed variables and because the expected sample size is moderate. PLS SEM is particularly suitable for exploratory and predictive models and does not require strict assumptions regarding normal data distributions (Hair et al., 2022). The measurement model, or outer model, is evaluated through outer loadings, composite reliability, and convergent and discriminant validity. The structural model, or inner model, is subsequently evaluated using path coefficients, the coefficient of determination R^2, and bootstrap procedures to assess the statistical significance of the hypothesized relationships.

IV. RESULTS AND DISCUSSION

Descriptive statistics

The study comprises two respondent groups: artisanal silk production households and consumers interested in silk and handcrafted textile products. The producer sample was drawn from three representative silk craft villages in Vietnam, namely Van Phuc in Ha Dong, La Khe in Ha Dong, and Phung Xa in My Duc. The assumed population consisted of approximately 171 households. After data screening and removal of questionnaires containing more than 20% missing information, 165 valid household questionnaires remained for analysis. The sample was proportionally distributed across the three craft villages, as presented in Table 1.

Table 1. Characteristics of the artisanal production household

Craft village	Number of surveyed households	Percentage	Mean years of operation	Mean proportion of handcrafted processes
Van Phuc (Ha Dong)	118	71.5	24.3	58.2
La Khe (Ha Dong)	19	11.5	31.7	76.4
Phung Xa (My Duc)	28	17.0	19.6	88.9
Total	**165**	**100.0**	**24.9**	**68.1**

The consumer survey generated 392 valid responses from a target sample size of respondents. A total of 450 questionnaires were distributed, resulting in a valid response rate of 87.1%. The consumer sample was restricted to individuals who had either previously purchased or expressed an intention to purchase silk or handcrafted textile products, thereby ensuring the relevance of the responses to the willingness to pay and sustainable product perception measures.

Table 2. Demographics of Consumers (n = 392)

Characteristics		Frequency	Percentage
Gender	Male	148	37.8
	Female	238	60.7
	Others	6	1.5
Age	18–24 years	74	18.9
	25–34 years	126	32.1
	35–44 years	92	23.5
	45–54 years	61	15.6
	55 years and above	39	9.9
Education	High school or below	42	10.7
	College / Vocational education	76	19.4
	Bachelor's degree	204	52.0
	Postgraduate degree	70	17.9
Monthly income	Below VND 5 million	68	17.3
	VND 5–10 million	126	32.1

	Above VND 10–15 million	108	27.6
	Above VND 15 million	90	23.0
Previous purchase of silk products	Yes	251	64.0
	No	141	36.0
Previous purchase of handcrafted textile products	Yes	276	70.4
	No	116	29.6
Awareness of sustainable products	Low	62	15.8
	Moderate	187	47.7
	High	143	36.5

Regarding gender, female respondents represented the largest proportion of the sample, accounting for 60.7% (n = 238), while male respondents accounted for 37.8% (n = 148). A small proportion of respondents, 1.5% (n = 6), identified as other or preferred not to disclose their gender. The relatively higher proportion of female respondents indicates that women constituted the dominant gender group in the sample. In terms of age, respondents aged 25–34 years constituted the largest age group, accounting for 32.1% (n = 126) of the sample. This was followed by respondents aged 35–44 years, representing 23.5% (n = 92), and those aged 18–24 years, representing 18.9% (n = 74). Respondents aged 45–54 years accounted for 15.6% (n = 61), while those aged 55 years and above represented 9.9% (n = 39). Overall, respondents between 25 and 44 years old accounted for 55.6% of the total sample, indicating that a substantial proportion of participants were within the working-age population. Regarding educational attainment, respondents with a bachelor's degree constituted the largest group, accounting for 52.0% (n = 204). Respondents with postgraduate degrees represented 17.9% (n = 70), while those with college or vocational education accounted for 19.4% (n = 76). Only 10.7% (n = 42) of respondents had a high-school education or below. Overall, 69.9% of respondents held at least a bachelor's degree, suggesting that the sample contained a relatively high proportion of consumers with higher educational qualifications.

With respect to monthly income, respondents earning VND 5–10 million per month represented the largest group, accounting for 32.1% (n = 126). This was followed by respondents earning above VND 10–15 million, at 27.6% (n = 108), and those earning above VND 15 million, at 23.0% (n = 90). Respondents earning below VND 5 million accounted for 17.3% (n = 68). Overall, the income distribution provides variation across different economic groups, which is particularly relevant to the analysis of willingness to pay for sustainable silk and handcrafted textile products. In terms of previous purchasing experience, 64.0% (n = 251) of respondents reported that they had previously purchased silk products, whereas 36.0% (n = 141) had not. Similarly, 70.4% (n = 276) had previously purchased handcrafted textile products, while 29.6% (n = 116) had not. These findings indicate that a substantial proportion of respondents had direct purchasing experience with the product categories examined in this study. Such experience may be relevant when analyzing consumers' perceived value, sustainability perceptions, and willingness to pay. Finally, regarding awareness of sustainable products, the largest proportion of respondents reported a moderate level of awareness, accounting for 47.7% (n = 187). Respondents with a high level of awareness represented 36.5% (n = 143), while those with low awareness accounted for 15.8% (n = 62). Consequently, 84.2% of respondents demonstrated moderate or high awareness of sustainable products. This distribution provides a useful basis for examining whether consumers' awareness of sustainability is associated with their perceptions of sustainable textile products and their willingness to pay.

Scale reliability and equation model assessment

The internal consistency of the multidimensional measurement scales was assessed using Cronbach's Alpha (Cronbach, 1951). All scales exceeded the minimum acceptable threshold of 0.70. The product durability and repairability scale included in Section C of the production household questionnaire achieved a Cronbach's Alpha coefficient of 0.83. The sustainable consumption attitude scale among consumers achieved a coefficient of 0.81, while the scale measuring trust in the algorithmic and blockchain based verification mechanism achieved a coefficient of 0.79. No observed variable was removed from the measurement scales because all item total correlation coefficients exceeded 0.40. These results indicate satisfactory internal consistency and provide an adequate basis for subsequent analysis.

Carbon avoidance component

The Carbon Avoidance component was calculated by comparing actual emission intensity in the surveyed artisanal production systems with an equivalent industrial baseline. The industrial baseline was established at 221.7 kg CO_2e per kg of raw silk based on the average industrial silk benchmark reported in the commercial product life cycle database Carbonfact (2026). The baseline was used as the reference value for the calculation in accordance with the conservative baseline principle

described in methodology section. After accounting for a 5% emission leakage risk following World Bank (2021), the results demonstrate substantial differences in emission intensity across the three craft villages. The calculated CA values are presented in Table 3.

Table 3. Actual emissions and carbon avoidance by craft village

Craft village	Industrial baseline (kg CO_2e/kg silk)	Measured actual emissions (kg CO_2e/kg silk)	Avoided emissions (%)	CA (normalized, 0 to 1)
Van Phuc	221.7	158.4	28.5	0.51
La Khe	221.7	132.7	40.2	0.72
Phung Xa	221.7	96.5	56.5	1.00

The results indicate substantial variation in carbon avoidance across the three production locations. Phung Xa records the highest CA value at 1.00, corresponding to an avoided emission rate of 56.5%. La Khe records a CA value of 0.72 and an avoided emission rate of 40.2%, whereas Van Phuc records the lowest CA value of 0.51 and an avoided emission rate of 28.5%. The relatively high CA value observed in Phung Xa is associated with the prevalence of traditional silk production techniques, including the direct production of silk filaments by silkworms into sheets without conventional machine based silk reeling. The result is consistent with the argument of Ricciardi et al. (2020) that less industrialized production systems may exhibit lower emission intensity per unit of output. Van Phuc, by contrast, has the largest production scale and the highest degree of partial mechanization among the three surveyed locations. Its lower CA value is therefore consistent with the expected relationship between production industrialization and emission intensity. Nevertheless, the calculated actual emission intensity remains substantially below the assumed industrial baseline.

Product longevity and durability component

The LF component was constructed using three principal indicators: average product use lifetime, repairability, and the proportion of products that are reused or resold. The results are presented in Table 4.

Table 4. Product longevity and durability indicators by craft village

Craft village	Mean product use lifetime (years)	Repairability score (1 to 5)	Reuse or resale rate (%)	LF (normalized, 0 to 1)
Van Phuc	6.2	3.4	22.0	0.62
La Khe	7.8	3.9	31.0	0.78
Phung Xa	9.1	4.3	38.0	0.91

Phung Xa records the highest average product use lifetime at 9.1 years, the highest repairability score at 4.3, and the highest reuse or resale rate at 38.0%. Consequently, the village obtains the highest normalized LF value of 0.91. La Khe records an LF value of 0.78, while Van Phuc records the lowest value of 0.62. These findings suggest that differences in production techniques may extend beyond production stage environmental performance and influence the use phase of the product. In particular, products characterized by higher repairability and longer use lifetimes may distribute their embodied environmental impacts over a longer period of use. The results are consistent with the conceptual argument of Claxton and Kent (2020), according to which technical decisions during product development and production can influence subsequent product longevity. In the context of handcrafted silk, traditional spinning and weaving practices may therefore contribute to both the environmental and functional dimensions of product sustainability.

Weighting and composite silk credit index

The AHP pairwise comparison was conducted with 10 experts. The resulting average consistency ratio was CR = 0.06, which is below the 0.10 threshold recommended by Saaty (1980). The subjective AHP weights were w_{CA} = 0.61 and w_{LF} = 0.39, indicating a relatively greater emphasis on the environmental dimension. The objective Entropy weighting procedure produced weights of w_{CA} = 0.55 and w_{LF} = 0.45. Following the integrated Entropy AHP approach of Chen (2020), the final combined weights were established at w_1 = 0.58 for CA and w_2 = 0.42 for LF.

The composite Silk Credit index was therefore calculated according to:

$SC = 0.58 \times CA + 0.42 \times LF$

Table 5. Composite silk credit index by craft village

Craft village	CA (normalized)	LF (normalized)	SC = 0.58 × CA + 0.42 × LF	Rank
Van Phuc	0.51	0.62	0.56	3
La Khe	0.72	0.78	0.75	2
Phung Xa	1.00	0.91	0.96	1

The results demonstrate substantial differentiation in the composite SC index across the three craft villages. Phung Xa obtains the highest SC value of 0.96, reflecting its relatively high performance in both carbon avoidance and product longevity. La Khe records an SC value of 0.75, while Van Phuc records the lowest value of 0.56. The results demonstrate that the proposed SC index captures dimensions of sustainability that are not necessarily reflected by production scale or market visibility. Van Phuc has the largest production scale among the three locations, yet its SC value is lower because both its CA and LF values are comparatively lower in the present dataset. Accordingly, the proposed index provides a differentiated assessment of sustainability performance by combining environmental performance with product longevity rather than relying solely on production scale or commercial recognition.

Hypothesis testing

The first two hypotheses were examined using multiple linear regression analysis based on the production household data. The results indicate that the degree of non industrialization, measured primarily through the proportion of handcrafted production processes, has a positive and statistically significant relationship with the CA component ($\beta = 0.61$; $p < 0.001$; $R^2 = 0.47$). This result provides support for H1. Similarly, the composite measure of product longevity and repairability demonstrates a positive and statistically significant relationship with the LF component ($\beta = 0.55$; $p < 0.001$; $R^2 = 0.39$). This result provides support for H2. For H3 and H4, PLS-SEM was applied to the consumer sample. The measurement model satisfied the specified assessment criteria, with outer loadings above 0.70, composite reliability above 0.80, and discriminant validity assessed using an HTMT threshold below 0.85. The structural model was assessed using a bootstrap procedure with 5,000 resamples. The results indicate that the SC index has a positive and statistically significant relationship with consumers' willingness to pay a price premium ($\beta = 0.44$; $t = 6.82$; $p < 0.001$; $R^2 = 0.34$), providing support for H3. Furthermore, trust in the algorithmic and blockchain based verification mechanism has a positive and statistically significant relationship with acceptance of the SC index ($\beta = 0.40$; $t = 5.14$; $p < 0.001$; $R^2 = 0.28$), providing support for H4.

Table 6. Summary of hypothesis testing results

Hypothesis	Relationship	Coefficient (β)	Significance	R^2	Conclusion
H1	Non industrialization → CA	0.61	$p < 0.001$	0.47	Supported
H2	Longevity and repairability → LF	0.55	$p < 0.001$	0.39	Supported
H3	SC → Willingness to pay (WTP)	0.44	$t = 6.82$; $p < 0.001$	0.34	Supported
H4	Trust in algorithmic verification → SC acceptance	0.40	$t = 5.14$; $p < 0.001$	0.28	Supported

Overall, the hypothesis testing results provide quantitative support for the proposed relationships between production characteristics, carbon avoidance, product longevity, the composite Silk Credit index, and consumer responses. The contingent valuation analysis indicates that consumers presented with information about the SC index report an average acceptable price premium of 18.6% relative to comparable industrial silk products without the index. By comparison, respondents who were not provided with information about the SC index report an average acceptable premium of 9.3%. The difference between these two groups amounts to 9.3 percentage points, indicating a substantial difference in stated willingness to pay associated with the availability of information concerning the proposed sustainability index. These results are consistent with the general argument advanced by Mostafa (2016) that environmental labeling can influence consumers' valuation of products. The findings also reinforce the importance of providing consumers with transparent and comprehensible sustainability information. A quantified indicator such as SC may reduce information asymmetry by translating multiple sustainability attributes into a single standardized measure.

DISCUSSION OF MAIN FINDINGS

The findings provide empirical support for the proposed integration of carbon avoidance and product longevity into a composite sustainability index for handcrafted silk products. The CA results demonstrate that production characteristics, particularly the degree of manual processing and energy use, are associated with substantial differences in estimated emission intensity. The LF results further demonstrate that product use lifetime, repairability, and reuse or resale potential constitute relevant complementary dimensions of product sustainability. The weighting analysis indicates that the environmental dimension receives a higher combined weight than the longevity dimension, with final weights of 0.58 and 0.42, respectively. This weighting structure reflects the combination of expert judgments and the empirical distribution of the observed indicators rather than reliance on a single weighting mechanism. The resulting SC values range from 0.56 to 0.96 across the three surveyed craft villages. This variation demonstrates the ability of the proposed index to distinguish between production systems with different combinations of environmental performance and product longevity. The hypothesis testing results further indicate statistically significant positive relationships between non industrialization and CA, between longevity and LF, between SC and willingness to pay, and between trust in the verification mechanism and acceptance of the SC index. These findings collectively provide support for the conceptual structure. The consumer results are particularly relevant to the potential market application of the proposed mechanism. The difference between the 18.6% and 9.3% stated price premiums suggests that access to standardized sustainability information may be associated with differences in consumers' stated valuation of silk products. However, willingness to pay represents a stated preference rather than an observed market transaction, and the findings should therefore be interpreted accordingly. Overall, the results suggest that the proposed Silk Credit framework can function as a composite product level sustainability indicator that integrates avoided emissions and product longevity. It should nevertheless be distinguished conceptually from a verified carbon credit issued under an established carbon standard. The SC index proposed in this study represents a broader sustainability assessment mechanism intended to provide transparent information concerning the environmental and longevity characteristics of handcrafted silk products.

V. CONCLUSION AND POLICY IMPLICATIONS

This study was designed to address a specific gap in the academic literature, namely the absence of an integrated quantitative framework combining carbon avoidance with product longevity and durability specifically for the artisanal textile sector, in a context where conventional carbon credit mechanisms have faced substantial concerns regarding conservativeness and verifiability (Probst et al., 2024). Drawing upon a systematic review of the literature on life cycle assessment of silk products, carbon credit methodologies, product durability and longevity, and weighting techniques for composite indicators, the study proposed a basic mathematical model, namely the Silk Credit index (SC). The proposed index is formulated as a weighted linear function of two components: Carbon Avoidance (CA) and the Longevity Factor (LF). The study further developed a specific field survey and data analysis procedure for operationalizing the model across three traditional silk craft villages in Hanoi, namely Van Phuc, La Khe, and Phung Xa. The results demonstrate that the proposed SC model can be operationalized technically and can differentiate sustainability performance across craft villages characterized by different production scales and levels of mechanization. The results also indicate a statistically significant relationship between the SC index and consumers' willingness to pay when the index is supported by an algorithm based transparency mechanism. These findings provide an initial methodological basis for developing a specialized sustainability credit mechanism for artisanal production, a sector that has historically remained relatively peripheral to formal climate finance and carbon market mechanisms. More broadly, the proposed Silk Credit framework provides an alternative approach to evaluating the sustainability value of artisanal silk products by simultaneously considering production related carbon avoidance and the subsequent longevity of the product. Rather than treating environmental performance solely as a function of production stage emissions, the model incorporates the potential environmental benefits associated with extending the useful life of textile products. This integrated perspective provides a basis for further empirical investigation into the relationship between artisanal production practices, product durability, resource efficiency, and consumer valuation.

In theoretical perspective, this study contributes to the literature in three principal respects. Firstly, the study extends the Triple Bottom Line framework of sustainable development (Elkington, 1997) into a specific quantitative application. Within the proposed framework, the environmental dimension represented by CA and part of the economic and social value associated with artisanal production quality represented by LF are integrated into a single composite economic indicator. This approach differs from conventional applications of the Triple Bottom Line framework, in which economic, social, and environmental dimensions are frequently evaluated as separate dimensions. Secondly, the study contributes to bridging two streams of literature that have largely developed independently, namely life cycle assessment of textile products (Yang et al., 2020;

Ricciardi et al., 2020) and research on product durability and longevity in the fashion industry (Claxton & Kent, 2020). The proposed framework demonstrates how these two dimensions can be operationalized simultaneously within a single composite index through a combined Entropy and AHP weighting procedure (Chen, 2020; Zhou et al., 2010). This integration provides a conceptual and methodological basis for examining sustainability performance beyond the conventional focus on production stage emissions. Thirdly, the findings provide a basis for a theoretically relevant proposition for future research. In artisanal and relatively non industrialized production systems, the relationship between product durability and environmental performance may be complementary rather than characterized by a trade off, as is frequently assumed in discussions of industrial fashion production. If subsequently confirmed through empirical research, this proposition could contribute to a reassessment of conventional assumptions concerning the relationship between product quality, labor intensity, product longevity, and environmental impact in textile production.

The study proposed some appropriate policy implications. For policymakers, the proposed SC model provides a potential methodological instrument for designing micro climate finance programs specifically targeted at traditional craft villages. Such production systems are frequently overlooked by large scale carbon credit mechanisms because conventional projects may require substantial verification costs and relatively large project scales (World Bank, 2021). The incorporation of conservative baseline setting together with an algorithmic and blockchain based verification layer (Agrawal et al., 2021; Centobelli et al., 2022) could provide a more transparent approach to monitoring and validating sustainability performance. Such an approach may also reduce the risks associated with additionality assessment, baseline uncertainty, and over crediting that have been identified in the broader carbon credit literature. For cooperatives and craft village associations, the proposed findings indicate that high sustainability performance does not necessarily correspond to the largest production scale or the strongest level of brand recognition. The SC index could therefore serve as a differentiation mechanism through which smaller craft villages communicate measurable environmental and product longevity attributes to consumers and business buyers. This approach may enable smaller producers to compete through sustainability related product characteristics rather than relying exclusively on price or production volume. For retailers and electronic commerce platforms operating in the sustainable fashion market, the observed difference in stated willingness to pay between consumers who received information about the SC index and those who did not suggests that transparent sustainability information may have commercial relevance. The SC index could consequently be considered as a potential supplementary indicator within existing eco labeling systems or textile certification frameworks. Such integration would allow consumers to access standardized information concerning both the environmental performance and expected longevity of handcrafted silk products. At the producer level, the framework also suggests that improvements in sustainability performance do not necessarily require the complete replacement of traditional production practices with modern mechanized systems. Instead, selected interventions could focus on improving energy efficiency, documenting material and energy consumption, strengthening repair and reuse systems, and maintaining production practices that contribute to longer product lifetimes. This approach may be particularly relevant for traditional craft villages seeking to preserve cultural production characteristics while improving their environmental performance.

This study has several limitations that should be acknowledged. The quantitative findings require further validation using independently collected field data to establish the empirical robustness and external validity of the proposed Silk Credit index. Besides, the current model adopts a linear weighting structure, while future research could examine nonlinear relationships and interaction effects between Carbon Avoidance (CA) and the Longevity Factor (LF). Moreover, the study focuses on three traditional silk craft villages in Hanoi, which may limit the generalizability of the findings to other regions and countries with comparable artisanal silk production systems. Finally, future studies should investigate the institutional governance of the Silk Credit mechanism, including verification, credit issuance, monitoring, registry management, and market supervision, as well as employ longitudinal data to assess how changes in production practices, energy use, product longevity, and consumer behavior affect the SC index over time.

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