Fleece Preparation Technology for Obtaining Fabric from Defective Cocoons

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Keywords: Defective Cocoons, Silk Waste, Silk Fleece, Nonwoven Fabric, Staple Length, Sericin Removal, Boiling Conditions, Fibre Length Distribution, Textile Recycling, Industrial Technology.

Abstract: The efficient utilization of silk-processing waste is essential for improving the resource efficiency and environmental sustainability of the textile industry. This study investigates a technology for producing silk fleece from defective cocoons of the Jingsong × Haoyue hybrid as a raw material for nonwoven fabrics. Unreelable cocoons were processed into silk fleece using an HL100 automatic silk wadding machine. The effects of alkaline soap-soda treatment and different boiling solutions on sericin removal and fibre quality were evaluated. The cocoon waste and prepared fleece were characterized by sorting statistics, microscopic examination of fibre arrangement, and fibre length analysis after cutting to staple lengths of 30, 35, and 40 mm. The results showed that double-dome, spotted, white-patch, and stalk-marked cocoons constituted the major defective fractions. Although unsuitable for conventional silk reeling, these cocoons proved suitable for fleece production. The optimal soda-soap boiling regime removed approximately 6-7% of sericin while preserving fibre integrity. Fibre length analysis revealed a predominance of very short (1-10 mm) and very long (≥70 mm) fibres, indicating limited suitability for spinning but good potential for nonwoven manufacturing. Two processing routes for nonwoven silk materials were proposed: incorporation of thermoplastic binder fibres and needle punching followed by heat pressing. The proposed technology enables the conversion of defective cocoon waste into value-added raw material for environmentally sustainable nonwoven silk products, contributing to waste valorization and circular resource utilization in the silk industry.

1 INTRODUCTION

The global textile industry generates large volumes of fibrous waste at all stages of the technological chain, from fibre production to fabric finishing. Natural fibres such as cotton, wool and silk are relatively expensive to produce, require significant land, water and energy inputs, and are often discarded after short periods of use, which exacerbates both economic losses and environmental burdens [1]-[4]. In particular, silk, as a high-value protein fibre, combines excellent aesthetic and functional properties with limited global supply and high market demand. As a result, any loss of silk in the form of production waste or post-consumer waste represents a considerable loss of embodied resources and economic value. Increasing the level of utilisation of silk waste and by-products is therefore a key direction for improving the resource efficiency and sustainability of the textile sector.

The concept of waste-free or low-waste textile technologies is becoming increasingly important in the context of circular economy strategies. A number of studies and industrial solutions focus on the collection, classification and re-use of fibrous waste generated at different stages of spinning, weaving, knitting and finishing processes [2], [4], [5]. For natural silk, however, the complete elimination of fibrous waste is technologically impossible because of the specific features of sericulture, cocoon formation and raw silk reeling. Defective cocoons, unreelable cocoons, reeling waste and various off-grade fractions inevitably arise and are traditionally underutilised or down-cycled. Transforming these low-grade resources into raw materials for high added-value products, such as nonwoven materials, is therefore an urgent scientific and practical task.

In sericulture and cocoon-reeling production, a substantial share of the incoming cocoon mass cannot be converted into high-quality raw silk owing to structural defects, biological factors or technological disturbances. According to production data for 2020, cocoon processing enterprises produced about 1200 t of raw silk (120 % growth compared to 2019), 800 t of silk canvas (118.7 %), 2557 thousand m² of silk fabric (118.9 %) and 800 t of silk waste (119.4 %). The total mass of silk fluff and silk waste thus exceeds the mass of raw silk obtained. A significant proportion of this waste is represented by defective and unreelable cocoons (double-dome, spotted, white-patch, stalk-marked and others), which are unsuitable for conventional reeling but retain a high content of valuable fibroin. This statistical picture clearly demonstrates the potential of defective cocoons as an abundant and underexploited source of raw material for new silk-based products.

From an applied-industry perspective, the problem of processing defective cocoons is directly linked to industrial resource efficiency, technological innovation and environmental risk reduction in textile manufacturing. The development of specialised technologies for converting cocoon waste into silk fleece and further into nonwoven fabrics allows enterprises to reduce the specific consumption of primary raw silk, expand the product range and increase profitability at relatively low capital costs. At the same time, the diversion of silk waste from low-value uses or disposal to high-value nonwoven applications mitigates the environmental impact in regions with a high concentration of silk enterprises. In this context, the creation and optimisation of process flows for preparing silk fleece from defective cocoons represent an important step towards sustainable industrial technologies that combine economic benefits with improved environmental performance.

2 LITERATURE REVIEW AND PROBLEM STATEMENT

The utilisation of silk-processing waste has attracted growing scientific interest owing to the increasing cost of natural fibres and the need to reduce the environmental footprint of textile production. Numerous studies have examined the structural changes of fibroin during chemical treatment of silk waste, demonstrating that appropriate solvent or alkaline systems allow the selective removal of sericin without degrading the fibroin backbone [2]. Such findings form the basis for developing technologies that convert low-grade silk waste into functional raw materials with added value.

Recent research has highlighted the significant potential of silk waste in the production of nonwoven materials, composite structures and regenerated fibres. Studies show that the recycling of silk waste can be economically feasible and environmentally beneficial given the persistently high demand for silk-based products in North America, Europe and the Asia-Pacific region [4], [5]. Depending on its origin, silk waste is categorised as sericulture waste, cocooning waste or reeling waste, and up to 70 % of this waste can be returned to industrial circulation if appropriate processing methods are applied [6]. Several researchers have focused on optimising the boiling and degumming processes for fibrous silk waste to ensure more efficient sericin removal while maintaining fibre strength [7].

Beyond conventional textile uses, silk waste has also been explored as a raw material for speciality applications. Short-fibre silk waste has been evaluated as a reinforcing component in paper production [8] and as a source for producing fibroin powders and nanoparticles through patented high-frequency or chemical precipitation methods [9]-[11]. In composite manufacturing, Tasar silk waste has been used as reinforcement in epoxy matrices, showing promising improvements in mechanical and tribological properties after surface modification, [12]. Nonwoven technologies are particularly effective for processing short and heterogeneous silk fibres. Air-laying, needle-punching and binder-based approaches have been used to produce nonwoven silk materials from reeling waste, pierced cocoons and other unsorted silk residues [13]. The resulting materials demonstrate useful properties for technical, filtration and oil-absorption applications [14]-[16]. In addition, chemical reduction methods enable the incorporation of silver or copper nanoparticles into silk-based nonwovens, producing antimicrobial surfaces with high porosity and dust-retention capacity [17], [18].

Studies in mixed-fibre yarns also confirm that blending silk waste with wool, polyester or synthetic fibres can improve strength, handle and appearance, indicating the versatility of silk waste as a functional additive [19], [20]. Research into regenerated silk fibres via dissolution in aqueous salts (e.g., $CaCl_2$), dialysis and electrospinning has further expanded the scope of silk waste utilisation in nanofibre production and biomedical applications [21]-[24]. These diverse technological directions illustrate the broad scientific interest in valorising silk waste and in developing efficient low-waste processing pathways.

Despite these advancements, several gaps remain. First, systematic studies on obtaining nonwoven materials specifically from defective and unreelable cocoons are limited, even though these cocoons represent a significant share of total silk-processing waste. Second, there is insufficient information on the industrial applicability of defective cocoons from specific hybrids, including the Jingsong × Haoyue variety, which has recently become widespread in regional sericulture. Third, a detailed analysis of fibre-length distribution, sericin content, and optimal boiling regimes for producing homogeneous silk fleece from defective cocoons is lacking. These technological parameters are critical for ensuring the quality of fleece intended for nonwoven fabric production.

Therefore, addressing these knowledge gaps is essential for developing a scientifically grounded, resource-efficient technology for converting defective cocoons into silk fleece and further into nonwoven materials suitable for industrial application.

3 THE AIM AND OBJECTIVES OF THE STUDY

The aim of this study is to develop and experimentally substantiate a resource-efficient technology for preparing silk fleece from defective and unreelable cocoons of the Jingsong × Haoyue hybrid for subsequent use in the production of nonwoven fabrics.

To achieve this aim, the following research objectives were defined:

- to classify defective cocoons of the Jingsong × Haoyue hybrid according to their types, frequency and contribution to total cocoon sorting waste;
- to examine the microstructure and fibre arrangement in graded, ungraded and defective cocoons in order to determine their technological suitability for fleece production;
- to investigate the effect of soap-soda boiling and auxiliary chemical treatments on sericin removal, fibre integrity and the overall quality of the obtained silk fleece;
- to determine the fibre-length distribution in the silk fleece after cutting to staple lengths of 30, 35 and 40 mm, and to assess its implications for nonwoven processing;
- to formulate and assess technological schemes for producing nonwoven materials from the prepared silk fleece using thermal bonding and needle-punching approaches.

This set of objectives ensures a comprehensive evaluation of defective cocoons as a viable raw material for industrial nonwoven silk production.

4 MATERIALS AND METHODS

4.1 Objects and Materials

The objects of the study were defective and unreelable cocoons of the *Jingsong × Haoyue* silkworm hybrid grown during the first rearing season in the Surkhandarya region. The cocoons were selected after industrial sorting and included double-dome, spotted, white-patch, stalk-marked and other defective types.

All chemical reagents were used as received without further purification. The main chemicals employed in the processing stages were:

- soap (40 % active substance);
- sodium carbonate (Na_2CO_3);
- hydrogen peroxide (H_2O_2, 2 g/L) used for bleaching;
- sodium bisulfite ($NaHSO_3$, 38 %) as an auxiliary reducing agent.

Water used in the technological processes met industrial soft-water standards.

4.2 Equipment

The following equipment was used in the preparation and characterization of silk fleece:

- HL100 automatic silk wadding machine (Hangzhou Hualong Weaving Machine Co. Ltd., China) - for forming the initial silk canvas (mat) from defective cocoons;
- HSG-10 boiling pot (Hyesung Machinery Co., South Korea) - for boiling, degumming and chemical treatment;
- DL-2500H horizontal compression rollers (DaeLim Starlet Co. Ltd., South Korea) - for compacting the boiled canvas;
- HE30 centrifuge (Han Seong Machinery Co. Ltd., South Korea) - for dewatering;
- DL-2004 light cocoon-sorting box (DaeLim Starlet Co. Ltd., South Korea) - for classification and visual inspection;

- ISM-DL300 INSIZE 3D microscope (Czech Republic) - for microstructural examination of cocoon shells at 100:1 magnification;
- SK-60H electronic scale (Harada Co. Ltd., Japan) - for measuring cocoon and fleece mass;
- Drum-type conditioning oven №128 (Harada Co. Ltd., Japan) - for determining cocoon moisture.

4.3 Formation of Silk Canvas on the HL100 Wadding Machine

Defective cocoons were fed onto the supply table of the HL100 machine. A heated alkaline solution containing 10 % soap (40 % active substance) and 0.5 % sodium carbonate was sprayed onto the cocoons at 60-70 °C for 10-12 min.

The alkaline treatment partially dissolved sericin, reduced fibre viscosity and facilitated the detachment of silk fibres from the cocoon shell. A mechanical restrictor blade prevented cocoons from becoming entangled in the forming mat. A uniform silk canvas layer was wrapped onto the rotating cylinder and subsequently removed for further processing.

4.4 Boiling and Chemical Treatment

The silk canvas was packed into individual porous bags and subjected to boiling in the HSG-10 vessel under the following controlled conditions:

- Boiling temperature: 97-98 °C;
- Boiling duration: 60 min;
- Liquor ratio (solution modulus): 50:1.

Three chemical compositions were investigated to evaluate their effect on sericin removal and fibre quality:

1) Solution 1: 40 % soap + 0.5 % sodium carbonate + 2 g/L H_2O_2
2) Solution 2: 5 g/L sodium carbonate
3) Solution 3: 10 g/L sodium carbonate + 4 mL/L sodium bisulfite (38 %)

Following boiling, the canvas was washed sequentially in hot (55-70 °C), warm and cold water to remove dissolved sericin and residual chemicals. The washed canvas was mechanically compressed to 100 % compression using DL-2500H rollers and then dehydrated in the HE30 centrifuge.

4.5 Fibre Parallelisation and Drying

During boiling, fibres became displaced and oriented irregularly due to swelling and relaxation of the cocoon shell. To ensure uniformity before staple cutting, the wet silk canvas was manually parallelised: one end of the fleece was fixed, while the opposite end was lightly shaken and rotated in air. This procedure was repeated for both sides and the central region of the fleece.

Drying was performed in a sheltered open-air environment with adequate natural ventilation. The fleece sheets were hung vertically to ensure uniform drying without deformation.

4.6 Staple-Length Preparation

After drying, the silk canvas was cut into staple lengths of 30 mm, 35 mm and 40 mm. From each sample, 300 individual fibres were randomly selected for length-distribution analysis. Fibres were spread on a black matte surface to enhance visibility and measured manually according to the method of Bhat and Basu [25].

4.7 Analytical and Measurement Methods

Cocoon sorting: Sorting of dry cocoon samples was performed according to the classification criteria described by Bhat and Basu [26], which allowed identification of graded, ungraded and defective cocoons.

Moisture content determination. Cocoon moisture was measured using a drum-type conditioning oven by determining mass loss after controlled drying.

Silk yield: The output of silk fluff was determined gravimetrically using an electronic analytical scale.

Microscopic examination: The arrangement of fibres in the shells of graded, ungraded and defective cocoons was studied using the ISM-DL300 INSIZE 3D microscope at 100× magnification, allowing the assessment of porosity, fibre density, damaged regions and structural irregularities.

Fibre-length analysis. After staple preparation, fibre length distributions were plotted to quantify the proportions of ultra-short fibres (1-10 mm), medium-length fibres, and ultra-long fibres (≥70 mm), which are critical indicators in evaluating suitability for nonwoven processing.

This integrated set of materials, equipment and methodological approaches provided the basis for characterising defective cocoons, optimising boiling and degumming conditions, and determining the technological suitability of the obtained silk fleece for the production of nonwoven fabrics.

5 RESULTS

5.1 Classification of Defective Cocoons

Industrial cocoon sorting of the *Jingsong* × *Haoyue* hybrid revealed that 6-12 % of the total cocoon mass consisted of ungraded and defective cocoons. The distribution of defect types is presented in Figure 1. The bar chart illustrates the proportional distribution of defective cocoon types observed in the *Jingsong* × *Haoyue* hybrid during industrial sorting. Double-dome cocoons constitute the largest share of defects, followed by spotted, white-patch and stalk-marked types, while other minor defects account for the remaining proportion. This classification demonstrates that structural abnormalities and biological inconsistencies significantly reduce the reelability of these cocoons, leading to their accumulation as waste. The resulting distribution highlights the importance of developing processing technologies that can effectively utilise these defect-rich cocoon fractions as alternative raw materials, particularly in nonwoven silk production.

5.2 Microstructural Characteristics of Graded and Defective Cocoons

The fibre arrangement within the cocoon shells was examined using a 3D optical microscope at 100× magnification. Representative micrographs are summarised in Table 1.

The data presented in Table 1 show that, despite the diversity of defect types, all defective cocoons exhibit common structural deviations compared to graded cocoons. Most notably, defective shells demonstrate reduced porosity, higher local fibre density, and irregular filament deposition across their cross-sections. These microstructural distortions restrict the penetration of water and steam during boiling, thereby preventing uniform sericin dissolution. As a consequence, fibres in defective cocoons tend to adhere more strongly in certain regions, leading to incomplete degumming, unstable filament separation and elevated thread-breakage rates during reeling. Such behaviour confirms that defective, spotted, deformed and stalk-marked

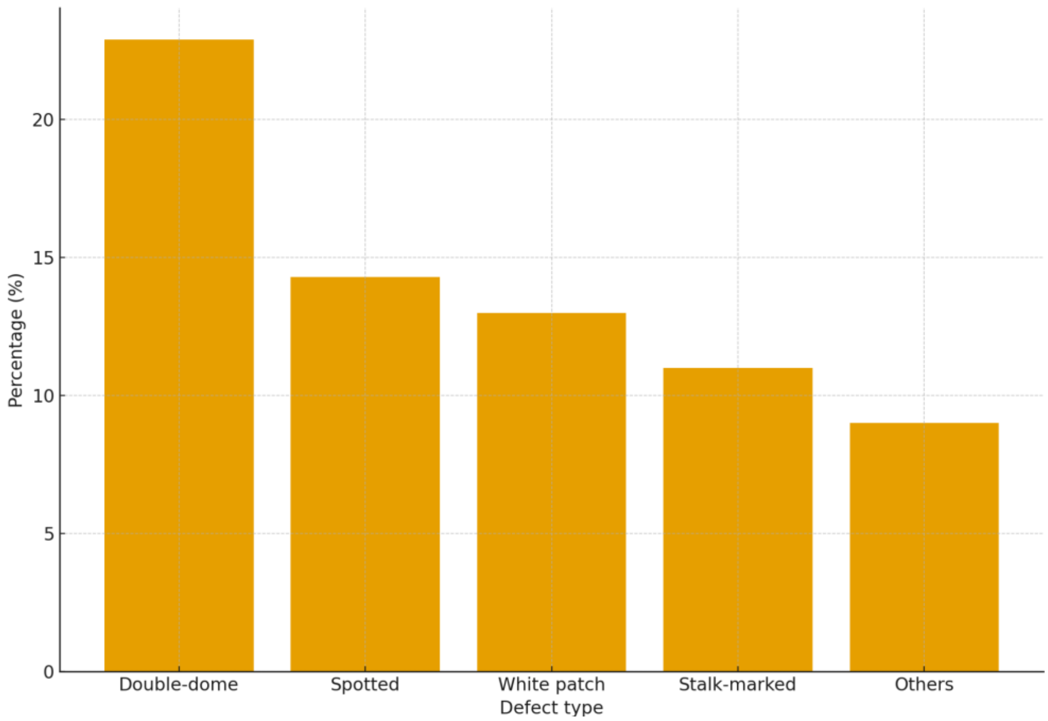


Figure 1: Percentage distribution of defective cocoons of the Jingsong × Haoyue hybrid: - double-dome cocoons - 22.9 %; - spotted cocoons - 14.3 %; - white-patch cocoons - 13.0 %; - stalk-marked cocoons - 11.0 %;,- other defects (pierced, hardened, malformed) - remaining share.

cocoons are technologically unsuitable for high-quality raw silk production, even though their fibroin content remains valuable. These findings form the basis for redirecting these cocoon fractions toward nonwoven fleece production, where fibre uniformity is less critical and irregular microstructure does not impede processing.

5.3 Extraction of Silk Fleece and Effect of Boiling Conditions

Silk canvas produced on the HL100 machine was subjected to boiling in three chemical compositions. The influence of the boiling solution on fibroin and sericin content, as well as degree of whiteness, is summarised in Table 2.

Table 1: Fibre arrangement and shell characteristics of graded, ungraded and defective cocoons.

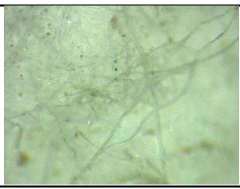
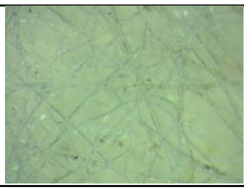
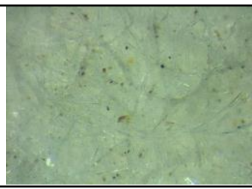
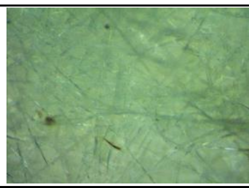
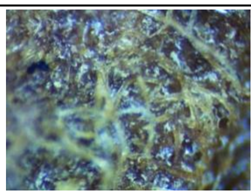
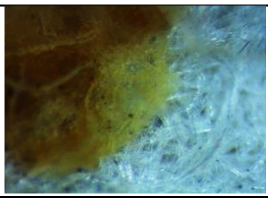
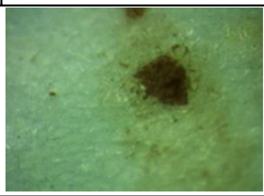
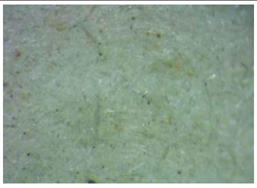
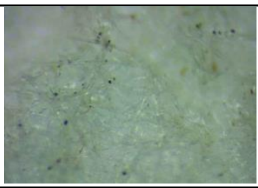
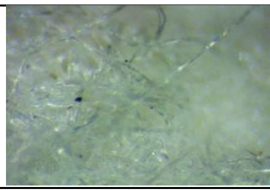
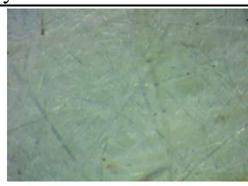
Shell appearance			
External look	Internal look	External look	Internal look
Double shelled		Deformed	
			
Lined		Spotted	
			
Inner spots		Smooth	
			
Thin shell		Variety	
			

Table 2: Influence of boiling solution composition on silk fleece properties.

№	Boiling solution	Fibroin, %	Sericin, %	Degree of whiteness, %
1.	Soap + Na_2CO_3 + H_2O_2	95.8	6.2	87
2.	Na_2CO_3 (5 g/L)	96.0	4.0	80
3.	Na_2CO_3 (10 g/L) + $NaHSO_3$	96.5	3.5	82

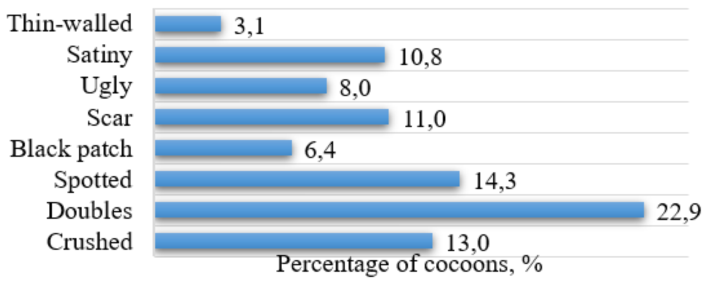


Figure 2: Silk fleece obtained from defective cocoons after the boiling and washing process.

Boiling in a soda-soap solution (Solution 1) resulted in acceptable sericin removal (≈6-7 %) while maintaining fibre integrity, making it optimal for nonwoven fleece production. Increasing alkalinity (Solutions 2 and 3) further reduced sericin content but negatively affected fibre strength and processing behaviour.

Figure 2 illustrates the general appearance of silk fleece obtained from defective cocoons after undergoing alkaline boiling, washing and mechanical dewatering. The fleece forms a continuous, lightweight, low-density fibrous web composed of irregularly oriented silk fibres loosened from the cocoon shell as a result of sericin dissolution. Its structure demonstrates the characteristic softness, bulk, and high porosity of degummed silk waste, indicating successful removal of surface impurities and partial sericin layers. The uniform light coloration of the fleece confirms effective chemical treatment, while the visible heterogeneity of the fibre bundle thickness reflects the intrinsic irregularity of defective cocoons. This material serves as the intermediate product intended for further parallelisation, staple cutting and nonwoven formation.

5.4 Fibre Parallelisation and Structural Behaviour

During boiling, fibres underwent displacement, leading to irregular orientation. Manual parallelisation aligned fibre bundles and reduced entanglement, which is necessary prior to cutting the fleece into staple lengths. Non-parallel fibres cause difficulties in carding, drafting and nonwoven web formation.

5.5 Fibre-length distribution in silk fleece

To evaluate the technological suitability of the fleece for nonwoven production, the material was cut into staple lengths of 30, 35 and 40 mm. From each sample, 300 individual fibres were measured. Fibre-length distribution results are presented in Figures 3-5.

Figure 3 illustrates the fibre-length distribution obtained from the silk fleece sample cut to a nominal staple length of 30 mm. The histogram reveals a pronounced heterogeneity in fibre size, with approximately 40 % of fibres deviating from the target length. Within this deviation, about 30 % of the fibres fall below the intended 30 mm cut, indicating the presence of numerous short and fragmented fibres resulting from irregular fibre orientation within the original cocoon structure. Additionally, nearly 10 % of fibres exceed the nominal length, confirming the presence of longer, continuous filaments that were not fully separated during canvas preparation. This uneven distribution demonstrates that the fibre mass derived from defective cocoons possesses inherently mixed lengths, which complicates spinning processes but remains acceptable for nonwoven fabric production where precise staple uniformity is not mandatory. Figure 4 presents the fibre-length distribution in the silk fleece sample cut to a nominal staple length of 35 mm. The results indicate that, despite increasing the target cutting length, the fibres still display a substantial deviation from the intended size. A considerable share of the fibres remains either ultra-short-originating from fragmented sections and weakly bonded regions of the cocoon shell-or ultra-long, representing incompletely separated filaments that remained intact during fleece preparation. The persistence of these two extreme fibre groups confirms that the initial structural heterogeneity of defective cocoons is preserved even after controlled staple cutting. Such variability highlights the challenges associated with producing uniform staple fibres from defective cocoon material and further supports the conclusion that this fleece is more suitable for nonwoven fabric technologies rather than spinning processes requiring tight length control.

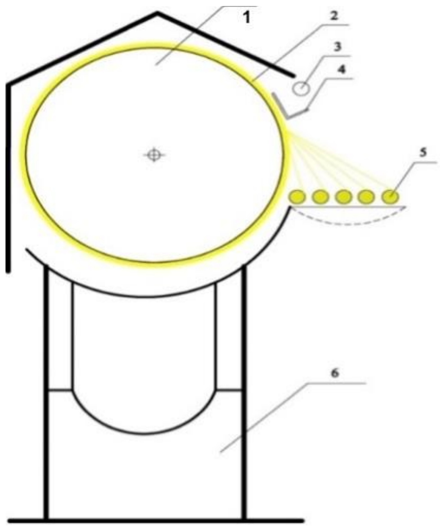


Figure 3: Fibre length distribution in 30-mm staple sample.

(a) (b)

Figure 4: Fibre length distribution in 35-mm staple sample.

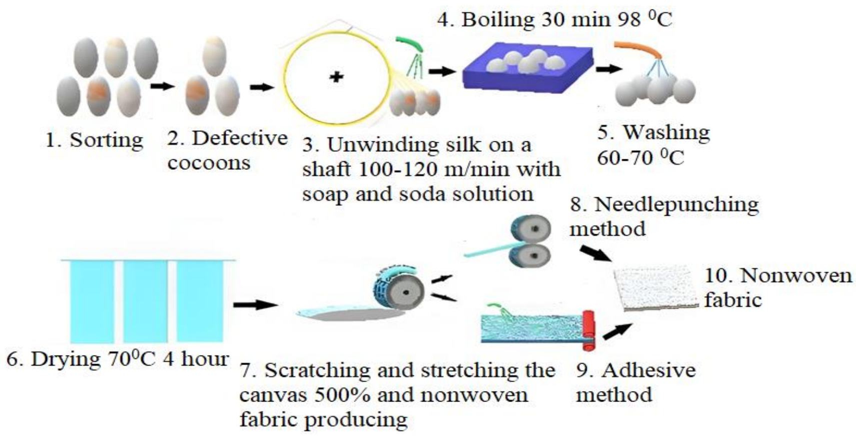


Figure 5: Fibre length distribution in 40-mm staple sample.

Figure 5 displays the fibre-length distribution in the silk fleece sample cut to a nominal staple length of 40 mm. The overall pattern remains consistent with previous samples, showing a markedly non-uniform distribution despite the increased cutting length. Fibres within the sample continue to exhibit strong heterogeneity, with a substantial portion deviating from the target length range. Notably, two recurring problematic groups are clearly visible: ultra-short fibres (1-10 mm) arising from fragmented or weakly structured cocoon sections, and ultra-long fibres (≥70 mm) representing continuous filaments that were not fully separated during canvas formation. The persistence of these extremes across all cutting lengths confirms that defective cocoons inherently produce heterogeneous fibre masses. This structural variability further supports the conclusion that such fleece is unsuitable for spinning applications requiring uniform staple fibres but remains viable for nonwoven technologies where fibre-length tolerance is significantly broader.

Their combined share exceeded expected norms by approximately 15 %, creating difficulties in drafting and spinning. This confirms that silk fleece from defective cocoons is unsuitable for conventional spinning, but remains appropriate for nonwoven fabric production, where fibre-length uniformity is less critical.

5.6 Technological Schemes for Producing Nonwoven Materials

Two approaches for processing silk fleece into nonwoven sheets were tested:

1) Mechanical stretching + thermoplastic binder fibres + thermal consolidation:
   - Fleece manually stretched in length and width;
   - thin layers formed;
   - bonded through heat treatment.
2) Needle-punching + heat-press strengthening:
   - Fleece thin enough to pass between needle plates;
   - mechanical entanglement achieved;
   - final consolidation via thermal pressing.

Both methods successfully produced nonwoven silk materials, demonstrating the technological feasibility of converting defective cocoons into value-added textile products.

This section demonstrates that defective *Jingsong × Haoyue* cocoons can be effectively transformed into silk fleece suitable for nonwoven applications, despite their heterogenous fibre structure and high proportion of sericin-derived defects.

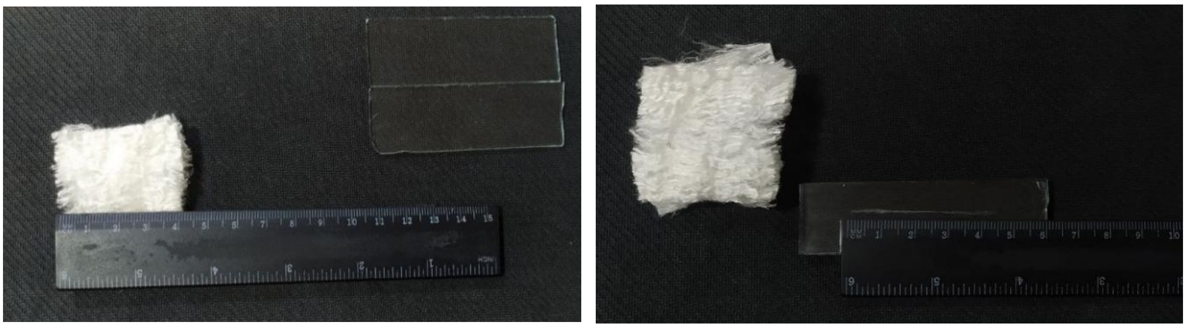
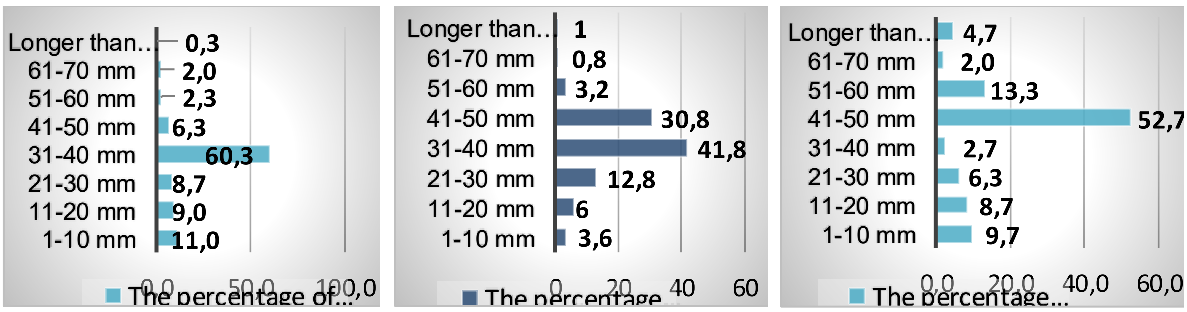


Figure 6: Analysis of the length of fibers in the sample.



(a) (b) (c)

Figure 7: Staple analysis of silk fibers: a - 30 mm, b-35 mm, c-40 mm.

Figure 6 demonstrates the preparation of silk fleece samples cut to nominal staple lengths of 30, 35, and 40 mm. These samples were obtained from a uniformly processed silk canvas derived from defective cocoons. The cutting process was carried out under controlled conditions to evaluate how fibre-length heterogeneity manifests after mechanical sectioning. Each sample served as a basis for subsequent microscopic and manual measurements. From every staple category, 300 individual fibres were extracted and laid onto a black contrasting surface to ensure precise length evaluation. This sampling procedure allows systematic analysis of fibre-length variability and provides foundational data for assessing the suitability of defective-cocoon fleece for spinning or nonwoven processing.

Figure 7 presents the staple-length analysis of fibres in three silk fleece samples cut to 30 mm, 35 mm, and 40 mm, respectively (a-c). The graphs reveal that all samples exhibit significant length heterogeneity regardless of nominal cutting size. For the 30-mm staple (Fig. 7a), approximately 40 % of fibres deviate from the target, including 30 % short fibres and 10 % long fibres. Similar patterns persist in the 35-mm (Fig. 7b) and 40-mm (Fig. 7c) samples, demonstrating that the irregular spatial arrangement of fibres within the canvas is not corrected by simple mechanical cutting. The presence of substantial amounts of ultra-short fibres (1-10 mm) and ultra-long fibres (≥70 mm) across all samples confirms that defective-cocoon fleece inherently produces non-uniform fibre masses, supporting the conclusion that such material is unsuitable for spinning but viable for nonwoven fabric production.

The results obtained in this study demonstrate that defective cocoons of the *Jingsong* × *Haoyue* hybrid exhibit pronounced structural irregularities, including reduced porosity, increased fibre density and heterogeneous filament arrangement, all of which make them unsuitable for traditional reeling. Despite these technological limitations, the defective cocoon shells produced a clean and workable silk fleece following controlled alkaline boiling and washing. However, fibre-length measurements across the 30-mm, 35-mm and 40-mm staple samples revealed a consistently high proportion of ultra-short (1-10 mm) and ultra-long (≥ 70 mm) fibres, indicating inherent length heterogeneity that cannot be eliminated through mechanical cutting. This variability confirms that such fleece cannot meet the strict uniformity requirements of spinning, yet remains highly appropriate for nonwoven material production, where fibre-length tolerance is considerably broader. Overall, the findings validate the technological feasibility of converting defective cocoons into silk fleece suitable for nonwoven applications, thereby providing a valuable utilization pathway for a waste stream traditionally considered unsuitable for high-value processing.

6 DISCUSSION

The conducted experiments demonstrate that defective and unreelable cocoons of the *Jingsong* × *Haoyue* hybrid present substantial structural deviations compared to graded cocoons, which explains their unsuitability for classical reeling processes. The microstructural observations revealed consistently reduced porosity, irregular filament layering, and increased local fibre density across all defective cocoon types. These characteristics are known to limit water penetration during boiling and hinder uniform sericin dissolution, a phenomenon also highlighted in earlier studies on silk waste degumming and reeling challenges [2], [7], [27]. The present findings therefore reinforce existing literature by confirming that mechanical and biological defects in cocoon shells directly translate into technological limitations during raw silk production.

Despite these constraints, the results indicate that defective cocoons retain a significant amount of recoverable fibroin, making them a valuable resource for alternative processing routes. The implemented alkaline-soap boiling regime (40 % soap, 0.5 % sodium carbonate, 97-98 °C, 50:1 liquor ratio) proved sufficiently effective to remove 6-7 % sericin while maintaining fibre integrity. These outcomes corroborate previous reports indicating that moderate alkaline concentrations enable sericin removal without excessive fibroin degradation [9], [28]. More aggressive alkaline conditions further reduced sericin levels to 3.5-4.0 %, yet simultaneously compromised fibre strength-an effect widely recognised in silk degumming studies involving carbonate-based agents [21], [22].

The subsequent staple-length analysis of fleece samples cut to 30, 35 and 40 mm revealed persistent fibre-length heterogeneity irrespective of the nominal cut length. In all cases, a sizeable fraction of fibres deviated from the target length, with ultra-short (1-10 mm) and ultra-long (≥70 mm) fibres consistently present in quantities exceeding acceptable limits for spinning applications. These findings indicate that fibre heterogeneity originates not from cutting technique, but from the inherent structural irregularities of defective cocoons and the carding-like behaviour of boiling-induced fibre loosening.

Similar patterns were reported in studies of silk waste carding, where irregular fibre detachment led to broad fibre-length distributions that hindered the production of uniform spun yarns [12], [13].

From a technological perspective, these outcomes underscore the limited suitability of defective-cocoon fleece for spinning, where strict control over staple length and fibre uniformity is required. However, they simultaneously confirm the material's strong potential for nonwoven applications. Nonwoven technologies-including thermal bonding and needle-punching-are significantly more tolerant of fibre-length variability and can effectively incorporate multi-modal distributions without compromising product functionality. Previous research has demonstrated the feasibility of producing oil-absorbent, antimicrobial, filtration and composite nonwoven materials from silk waste, with performance characteristics heavily dependent on fibre fineness and chemical purity rather than length uniformity [14]-[18]. The present study aligns with these findings and provides experimental evidence that defective-cocoon fleece, once degummed and prepared under controlled conditions, constitutes a viable raw material for such applications.

Furthermore, the conversion of defective cocoons into nonwoven silk products presents economic and environmental benefits. Industrial cocoon-sorting data show that waste from defective cocoons can reach 6-12 % of the total cocoon mass, representing a considerable underutilised resource. Redirecting this fraction from low-value uses toward nonwoven production increases material recovery, reduces solid waste, and supports more sustainable processing in regions with high sericultural activity. This aligns with the global trend toward circular textile technologies, where fibrous by-products and waste streams are transformed into functional value-added materials [4], [5], [29].

Overall, the results of this study provide a scientifically grounded rationale for the development of a dedicated technological pathway for processing defective cocoons into nonwoven silk products. The findings confirm that while these cocoons are unsuitable for traditional reeling and spinning, they remain a rich and promising source of fibroin for nonwoven material manufacturing, thereby expanding the industrial utilisation of sericultural waste.

7 CONCLUSIONS

Industrial sorting of Jingsong × Haoyue cocoons showed that 6-12 % of the total cocoon mass consists of ungraded and defective cocoons, dominated by double-dome, spotted, white-patch and stalk-marked types. Microscopic examination confirmed that these defect types share common structural deviations from graded cocoons - reduced shell porosity, higher local fibre density and irregular filament deposition - which restrict water and steam penetration during boiling and explain their unsuitability for conventional reeling despite their retained fibroin content.

Among the three boiling compositions tested, the soap-soda-hydrogen-peroxide solution (Solution 1: 40 % soap, 0.5 % sodium carbonate, 2 g/L H_2O_2) provided the best balance between sericin removal and fibre integrity, removing approximately 6-7 % sericin while keeping the fibres mechanically sound. The more alkaline compositions (Solutions 2 and 3) achieved lower residual sericin (3.5-4.0 %) but at the cost of reduced fibre strength, indicating that moderate alkalinity is preferable for fleece intended for nonwoven processing.

Fibre-length analysis of the fleece cut to 30, 35 and 40 mm staple lengths consistently revealed a high proportion of ultra-short (1-10 mm) and ultra-long (≥70 mm) fibres, with roughly 40 % of fibres deviating from the nominal cut length regardless of the staple setting. This inherent heterogeneity, originating from the irregular structure of defective cocoons rather than from the cutting procedure itself, makes the fleece unsuitable for conventional spinning but fully compatible with nonwoven manufacturing, where strict length uniformity is not required.

Both nonwoven-forming routes examined - thermal bonding with thermoplastic binder fibres and needle-punching with heat-press consolidation - were technologically feasible for converting the prepared silk fleece into coherent nonwoven sheets. Taken together, these results demonstrate that defective and unreelable Jingsong × Haoyue cocoons, previously regarded as low-value waste, can be converted through a straightforward alkaline boiling and mechanical processing sequence into a viable raw material for nonwoven silk products, supporting resource-efficient and environmentally sustainable practices in sericulture and silk processing.

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