



Thermal comfort properties of silk fabrics dyed using natural extracts

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In this study, commercially acquired mulberry silk cut filaments are processed into 100% spun silk yarns and subsequently woven into fabrics using traditional underpick looms with uniform warp and weft. The fabrics are dyed with pomegranate peels without mordanting. Twenty-seven silk fabric samples are produced, with varying dye concentrations and dyeing durations (1-3 concentrations across 3, 6, and 12 h). The investigation aims to analyse the effect of dyeing parameters on the thermal comfort properties of the resulting fabrics, thereby offering insights into dye-fibre interactions and their influence on the final thermal characteristics. The results prove that the samples dyed at lesser concentrations, shorter durations and under lowered pH conditions possess better thermal comfort properties.

Keywords: Comfort, Dyed silk yarn, Pomegranate, Thermal comfort

1 Introduction

Clothing comfort is a basic consumer need characterised as a pleasant feeling brought on by the physiological, psychological, and physical harmony between a person and their environment. The literature frequently divides clothing comfort into three main categories: thermo-physiological, tactile, and aesthetic. Subjective emotions and current fashion trends mostly define aesthetic attractiveness or psychological comforts and impact consumer choices. Thermophysiological comfort, on the other hand, is the capacity of the fabric to maintain thermal stability between the human body and the environment. Clothing comfort is a basic human requirement that emanates from the balance of physiological, psychological, and physical interactions with the environment. Usually, comfort is categorised into fewer than three: thermo-physiological comfort, tactile comfort, and aesthetic/psychological comfort. Thermo-physiological comfort holds considerable importance as it regulates heat and moisture depending on fabric parameters such as air permeability, water vapour permeability, thermal conductivity, and thermal resistance.

Silk is a natural protein fibre, highly valued for its lustre, softness, draping qualities, and natural thermal

regulation. It keeps you warm in winter and cool in summer due to its high capacity for moisture absorption. Increasing costs of silk and the reliance on synthetic dyes, however, are encouraging people to seek greener alternatives. Thermophysiological comfort of the wearer is influenced by the material's thermal, moisture, and air resistance properties. The feeling of fabric against the body is called tactile comfort, a fundamental and essential performance standard in clothing. In order to study the tactile properties of fabrics, such as bending and drape, several methods have been created¹⁻². According to their grandeur, adaptability, wearability, and comfort, silk fabrics are regarded. It retains heat in the winter and coolness in the summer by absorbing moisture. It has excellent shape retention, a lovely drape, and gorgeous glitter. Despite having so many positive qualities, silk is relatively pricey. As the cost of silk fabric continues to increase, the demand for mixed silk fabric is expected to increase. Due to this, hybrid silk-synthetic fabrics are now more widely used³⁻⁶.

2 Materials and Methods

2.1 Materials

Commercially available mulberry silk cut filaments were acquired from a silk processing mill in Karnataka, India. These cut filaments were transformed into 100 % spun silk and subsequently woven into plain-woven fabrics using traditional

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under-pick looms, maintaining identical warp and weft densities. Pomegranate peels were chosen for the dyeing process without using mordants. A total of 27 samples were prepared. The samples were dyed using aqueous extracts of pomegranate peel at three different concentration levels: 1 %, 2 %, and 3 % (w/v). For each concentration, dyeing was conducted at three different time durations: 3 h, 6 h, and 12 h and at three pH levels: 4.0, 4.5, and 5.0, resulting in 27 unique treatment combinations.

Mulberry silk cut filaments (length 42 mm, denier 1.2, tenacity 3.2 g/d, elongation 16 %) were obtained from a processing mill in Karnataka, India. These were spun into 100 % silk yarns (64.4 Ne count, CV % 1.8, Rkm 16.4 g/tex, U % 12.5, total imperfections 78/km) and woven into plain fabrics on traditional underpick looms. The fabric weighed 76.2 g/m², 35 ends/cm, and 26 picks/cm. Pomegranate peel was selected as the dye source. A total of 27 samples were dyed at three concentrations (1 %, 2 %, 3 %), three durations (3, 6, 12 h), and three pH levels (4.0, 4.5, 5.0), without mordants.

2.2 Air Permeability Test

The air permeability of the pomegranate extract-treated fabrics at varied concentrations and timing was evaluated using the KES-F8 AP1, Air Permeability Tester, in compliance with British Standard BS 5636 1990.

2.3 Thermal Conductivity and Resistance

The thermal conductivity of the fabric was assessed using Lee's disk instrument in accordance with the ASTM D7340 standard. Thermal conductivity, a fabric characteristic, quantifies the heat flux traversing the fabric sample under a specific

temperature gradient. Thermal resistance serves as an indicative measure, particularly applicable to insulation materials.

$$\text{Thermal resistance (R)} = h / \lambda \text{ (m}^2\text{K/W)} \quad \dots(1)$$

where h is the fabric thickness (m); and λ, thermal conductivity (W/mK).

2.4 Water Vapour Permeability

The fabric's water vapour permeability was assessed following the British Standard, BS 7109:1990. In this procedure, the fabric sample is positioned over the open mouth of a standard test dish containing water. The dish is then situated in a controlled environment at 20 °C and 65 % relative humidity for one hour. After each cycle, the weight of all fabric samples was measured.

3 Results and Discussion

3.1 Air Permeability

As seen in Figure 1, silk fabric dyed with pomegranate peel extract leads to a decrease in air permeability. This extract, like other natural dyeing agents, might adhere to the silk fibre surfaces and fill the gaps between those fibres¹². This results in a modest increase in coating density and alters the structure of the fabric, potentially affecting its air permeability. During dyeing, silk fibres swell upon absorbing dye molecules and moisture, temporarily altering the fabric structure and affecting air permeability. Tannins in pomegranate peel extract sometimes interact with silk fibres, changing their physical qualities and contributing to reduced porosity through fibre swelling, surface coating, and potential pore blockage¹⁵.

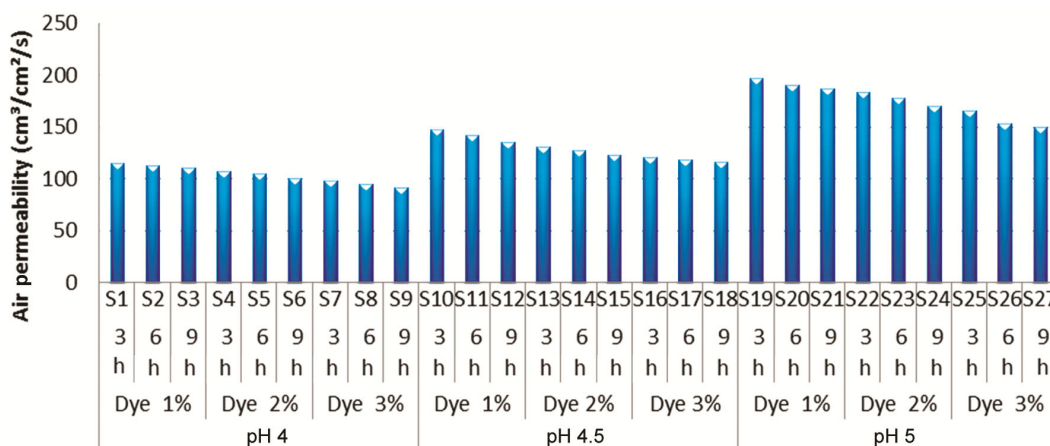


Fig. 1 — Air permeability of the silk fabrics under varying conditions

The amount of pomegranate peel extract used in dyeing can impact air permeability. Higher concentrations may produce a more prominent effect. The extent of air permeability is also influenced by pH level. The dye molecules may attach more tightly to the fibres in particular pH ranges, resulting in a denser coating on the fabric's surface¹². This higher coating density could narrow the gaps between individual silk fibres, affecting air permeability. At pH 4, dye molecules exhibit a higher affinity for silk fibres, forming a denser coating. As the dye concentration increases and the dyeing timing increases, the affinity of the dye molecules to the surface of the fabric is high. Also, this dye fixation plays a predominant role in the air permeability of the fabric. Sample S9 (3% concentration, 12 h, pH 4.0), dyed at a higher concentration and longer duration under acidic conditions, shows the lowest air permeability due to varied reasons such as increased coating density, stronger fibre-dye interactions, fabric swelling, pore blockage, etc. In contrast, Sample S19 (1% concentration, 3 h, pH 5.0), treated under milder dyeing conditions (pH 5.0, 1% dye concentration and reduced duration), retains appreciable air permeability¹⁶. This could be attributed to lower dye-fibre affinity, resulting in minimal obstruction to air flow and preservation of the fabric's breathable nature⁶⁻⁹.

3.2 Water Vapour Permeability

Water vapour permeability, measured as the rate of moisture transport through a material under a humidity gradient, is significantly influenced by the dyeing conditions. As seen in Figure 2, silk fabrics dyed with pomegranate peel extract exhibit varying levels of permeability depending on the dye concentration, pH, and duration.

Natural chemicals in pomegranate peel extract, such as tannins and polyphenols, interact with silk fibres and potentially alter their structure, influencing water vapour permeability. Silk fibres are sensitive to pH fluctuations. The pH of the dyeing process can influence dye molecule uptake by silk fabric. The dye molecules may bind differently to the silk fibres depending on the pH, potentially resulting in differences in dye coverage and distribution^{13,14}. This may indirectly affect the fabric's water vapour permeability. Following dyeing, the silk fabric goes through post-treatment treatments such as rinsing, washing, or dye fixing. These treatments may also impact the fabric's water vapour permeability. In this study, at pH 4, dye molecules demonstrate strong binding to silk fibres, particularly under higher concentrations and dyeing durations. As the concentration of dye increases and the dyeing process is extended, a clear trend emerges: the affinity of the dye molecules for the fabric surface becomes increasingly pronounced. This leads to increased coating density, reduced pore space, and, consequently, restricted moisture transport. (Fig. 2).

Figure 2 shows the outcomes of the experiments, which underscore the substantial impact of dye fixation on the fabric's water vapour permeability. Specifically, the research findings highlight that fabrics with higher concentrations of dye in an acidic environment (pH) and longer dyeing durations exhibit a restricted level of water vapour permeability. Several factors contribute to this outcome, including coating density, the interaction between the dye and the fabric's fibres, fabric swelling, and pore blockage, among others.

Notably, the research reveals a noteworthy pattern: fabrics subjected to a less acidic environment

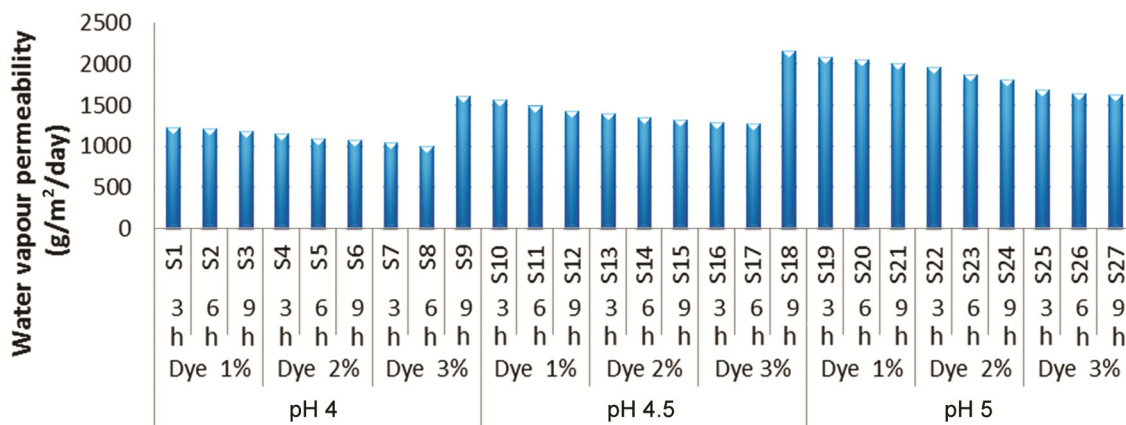


Fig. 2 — Water vapour permeability of the silk fabrics under varying conditions

and dyed with a concentration of 1% and a shorter dyeing duration exhibit a more favourable level of water vapour permeability. This can be attributed to the fact that the affinity of dye molecules to the silk fabric is comparatively lower under these conditions. Significantly, this reduced affinity does not compromise the fabric's inherent permeable nature.

The experimentation conducted at a pH of 4 highlights the intricate interplay between dyeing conditions and water vapour permeability in silk fabrics. The observations emphasise that while higher concentrations of dye and prolonged dyeing durations may enhance dye fixation, they can also lead to reduced water vapour permeability due to various factors affecting fabric structure and characteristics. On the other hand, achieving optimal water vapour permeability can be attained by strategically balancing dye concentration, dyeing duration, and pH levels to ensure that the fabric maintains its permeable attributes without compromising dye fixation⁶⁻⁹.

3.3 Thermal Conductivity

Thermal conductivity, a measure of heat transfer through a material, is notably affected by the structural changes induced by dyeing. Figure 3 shows that dyeing silk fibres with pomegranate peel extract alters the heat conduction behaviour due to physical and chemical interactions between dye molecules and silk fibres.

At pH 4, the dye molecules interact chemically and physically with the silk fibres, leading to the molecular and structural rearrangement of silk fibres and possible hydrogen bonding modifications. These changes influence the heat-carrying paths within the

fabric by increasing fabric density or blocking porous regions, thus reducing the fabric's capacity to conduct heat.¹⁷

Moreover, dyeing silk fabric may cause the fibres to inflate due to colour absorption and the dyeing process. This swelling can affect the fabric's microstructure, affecting heat conduction channels. It may also influence the phonon and electron transport pathways, contributing to thermal conductivity. Silk fabric dyeing may change its fibres' alignment and anisotropy (directional dependency). Depending on the direction of heat movement, fibre alignment changes could cause thermal conductivity variations. Sample S19, dyed at pH 5 for 3 h with 1% dye concentration, exhibits relatively higher thermal conductivity. This suggests moderate dyeing conditions preserve favourable fibre alignment and fabric porosity, enhancing heat transfer through the material.

3.4 Thermal Resistance

Thermal resistance, the inverse of thermal conductivity, quantifies a material's ability to resist heat transfer. The dyeing process impacts this property through modifications in surface characteristics, coating thickness, and internal fibre arrangement (Fig. 4).

At pH 4 and high dye concentration, dye molecules form a dense coating that acts as an insulating layer, increasing the material's resistance to heat flow. Additionally, swelling of fibres and blocked pores further contribute to a reduction in thermal conductivity and, thus, a rise in thermal resistance. Sample S9 treated under such conditions (3 % dye concentration, 9 h duration) shows higher thermal

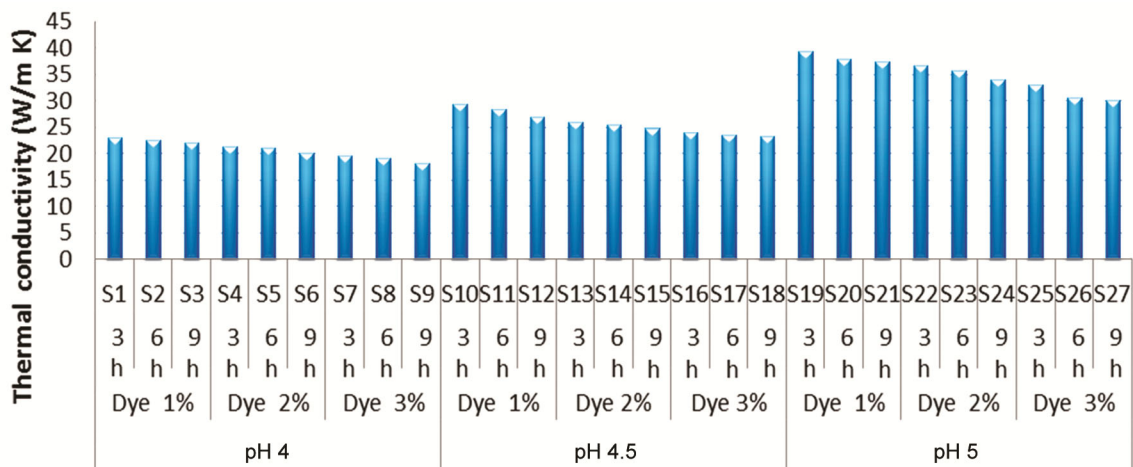


Fig. 3 — Thermal conductivity of the silk fabrics under varying conditions

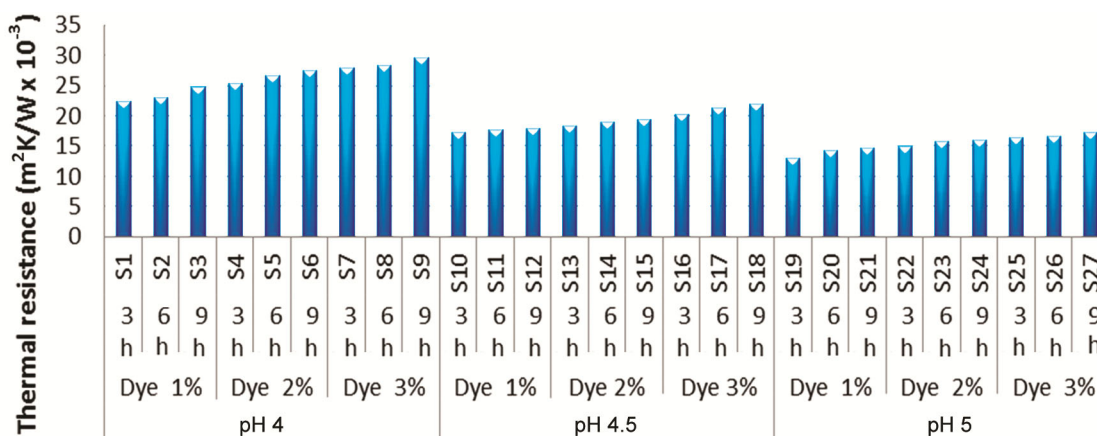


Fig. 4 — Thermal resistance of the fabric

resistance. The insulating effect is pronounced due to strong dye-fibre affinity and thick surface coverage¹⁷.

4 Conclusion

The study demonstrates that dyeing silk fabric with pomegranate peel extract significantly influences key comfort-related properties such as air permeability, water vapour permeability, thermal conductivity, and thermal resistance. The interaction between dye concentration, dyeing duration, and pH level, particularly the acidic condition at pH 4, profoundly affects the fabric's microstructure and functional performance. At pH 4, dye molecules have a great affinity for silk, resulting in denser fabric coatings, fibre swelling, and partial pore blockage. These structural changes contribute to reduced air and water vapour permeability, as well as altered thermal behaviour. Samples dyed under such conditions, especially with higher concentrations and longer durations, show hindered breathability and elevated thermal resistance. On the other hand, fabric samples exposed to less acidic conditions and dyed at lower percentages exhibit increased air permeability and more favourable thermal profiles without significantly compromising dye fixation. Due to characteristics such as coating density, fibre interactions, and pore blockage, fabrics with higher dye concentrations and longer dyeing at acidic pH have reduced water vapour permeability. This highlights the need for balance in dyeing parameters to optimise fabric comfort and functional performance. The study highlights the complex interactions between fabric characteristics, dyeing factors, and performance aspects and the

careful optimisation of dye concentration, pH, and dyeing time to achieve the required silk fabric properties.

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