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Moisture transport properties of knitted Tencel-polypropylene blends

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- For the intended application of inner gloves

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ABSTRACT

Sweat accumulation inside protective gloves can lead to skin issues such as hand eczema during prolonged use, due to the lack of moisture evaporation. To address this problem, inner gloves are intended to be used under protective gloves to transport moisture away from the skin, thereby promoting dryness. This study investigates how different material compositions, specifically blends of hydrophilic Tencel and hydrophobic polypropylene and various knitted structures influence moisture transport properties. Conducted in collaboration with DRYE AB, seeking to improve their current inner glove product. This study uses a quantitative approach and focuses only on fabric-level testing rather than full glove prototypes. Fabric samples were produced using circular knitting with different machine parameters. The moisture transport behaviour was evaluated using vertical and horizontal wicking test methods, with deionised water, acidic- and alkaline sweat solution as test media. The results show that altering machine parameters to manipulate material distribution during knitting was not effective. However, both material composition and knitted structures significantly influenced moisture transport. No substantial differences were observed between the sweat solutions and water. These findings further contribute to the development of more effective inner gloves for occupational settings by emphasizing the importance of material and knitted structures for improved moisture management.

Popular abstract

Wearing protective gloves for long periods often makes hands sweaty, and when the sweat is not able to evaporate, it can cause skin problems like irritation and hand eczema. This study looks at how to solve that by using thin inner gloves that helps move sweat away from the skin keeping the hands drier and healthier during work. The study was carried out in collaboration with DRYE AB, that wants to improve the moisture-handling properties of the inner gloves they currently produce. Together, we explored different fabric combination made from Tencel, which absorb moisture, and polypropylene, which repels it. These materials were knitted various ways to find out which blends and structures transport moisture most effectively. Instead of testing full glove prototypes, this study focused on lab tests of the fabrics alone. The materials were exposed to water, as well as artificial sweat, both acidic and alkaline, to see if the liquid type made a difference. The results showed that material choice and fabric structure have a big effect on how well moisture moves through fabric. Trying to change how the yarns were distributed in the knitting machine did not work as intended, but the right fibre blend and knit pattern made a clear difference. The type of liquid used, sweat or water, didn't significantly affect the results.

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1. INTRODUCTION

The hands play an important role in nearly every occupation task and ensuring their protection is an important factor in maintaining worker health, safety and performance. When properly designed, handwear can improve physical activities and reduce injury risks, while inadequate gloves may contribute to serious harm or even mission failures (Santee, Potter & Friedl 2017). Hand injuries can result in long term consequences, such as increased sensitivity to cold or in severe cases, permanent tissue damage. These issues are particularly relevant for occupational workers, who often face not only ergonomic stressors, like repetitive motions and mechanical hazards, but also environmental challenges such as exposure to cold and moisture. These factors are major contributor to hand related injuries and illnesses, which in turn lead to increased healthcare costs and lost productivity (Heberger, Naswarwanji, Pollard & Kocher 2022; Joshi, Li Wu, Zhang & Song 2024). Reduced hand functionality under these conditions can further increase the risk of accidents and reinjury. Yet, for many workers, including those in mining, construction and cold-storage industries, exposure to such environments is unavoidable. Protecting these individuals are important for maintaining both health and job performance (Joshi et al. 2024). While researcher have explored various factor influencing the clothing microclimate, such as body posture, moisture presence and anatomical differences (Mah & Song 2010), the microclimate inside protective gloves remains an unexplored area. This gap in knowledge is particularly significant, as the inner glove environment directly affects comfort, skin condition and functional performance during prolonged wear in demanding conditions (Joshi et al. 2024).

Wet work tasks, such as dishwashing and handling of chemicals, are the most common exposures leading to occupational irritant contact dermatitis. Use of liquid-proof gloves is recommended when performing wet work, however, gloves may also contribute to impairment of the skin barrier and development of irritant contact dermatitis (Tiedemann 2016). To address this challenge, the development of inner gloves that can transport moisture away is important. The effectiveness of such a glove depends on several factors, including material composition, knitting structures and finishing processes, all of which influence moisture management and bacterial growth (Paul 2019). Inner gloves are intended to be used under protective gloves to absorb moisture away from the skin and promote dryness on the hand.

The goal of this project is to develop knitted fabrics for the intended application of inner gloves, with improved moisture transportation properties, by focusing on material composition, knitting structures and finishing process. This research was proposed by DRYE AB, a company that provides inner gloves for occupational groups who wear protective gloves daily. The current fabric in the glove is made of a single jersey knit of Tencel and polypropylene. While this product is functional, the company seeks to optimise the fabric by improving its moisture wicking performance through this research.

1.1 Problem description

According to Arbetsmiljöverket (2012), approximately 10% of the population in Sweden suffer from hand eczema. Among these individuals, the majority are exposed to wet work, chemicals and allergies daily during their work. Occupational groups such as healthcare workers, industrial workers, hairdressers and mechanical workers to name a few, require the use of protective gloves. These groups often face issues to discomfort, skin irritation and potential health risks due to prolonged glove usage. A key factor contributing to these problems is moisture buildup inside the glove, which can lead to excessive sweating, bacterial growth and an overall reduction in comfort and hygiene. The discomfort caused by skin damage and itching is likely to affect the quality of life of healthcare workers (Sawada 2023). A review by Armstrong, Hahn-Pedersen, Barlett, Glanville and Thyssen (2022), confirmed that chronic hand eczema has an economic burden on society and health. The review covers Europe, Australia, New Zealand and America. Among the patients in the review, it reported up to 57% had to take sick leave and 25% had lost their job due to the need of changing profession, caused by chronic hand eczema. Given that some occupational groups have increased risks of developing skin issues on hands, it is clear that it has both an economic and societal burden to society caused by sick leave, medical costs and even job loss (Armstrong et al. 2022). This emphasis that functional inner gloves are needed for a group of people that suffer but also have increased chance of developing skin issues related to excessive or prolonged wearing of protective gloves. If a product can facilitate in minimizing chronic hand eczema, it gains both the individual but also decreases the burden for society.

1.2 Aim & scope

The aim of this project is to develop fabrics with improved moisture transportation properties for the application of inner gloves. The research investigates how different knitted structures and material composition, specifically blends of Tencel and polypropylene, affect moisture transport performance. The goal is to compare and find the optimal combination of moisture transport among the samples.

The scope of the study is limited to the evaluation of fabric samples only, without including full glove prototypes or user testing in terms of comfort. It focuses on quantitative laboratory testing of knitted fabrics. This research will examine; the influence of knitted structures on capillary wicking, the effect of material composition on moisture transport and the comparative performance of liquid transport using water and artificial sweat as testing mediums.

1.3 Research questions

1. How is the percentage-wise composition of Tencel and polypropylene affected by a) different bindings and adjustments in b) machine parameters and c) yarn feeding positioning?
2. How does the fibre composition of polypropylene and Tencel affect moisture transport?
3. How does fabric structure affect the moisture transportation properties?

4. How do moisture transport properties differ when tested with water vs. sweat?

1.4 Limitations

This research will only focus on two fibre types, Tencel and polypropylene and one yarn count for each fibre type will only be utilised. Other yarn counts will not be explored due to the limited availability. The circular knitting machine settings are restricted to gauge E12 and E20. Additionally, this research is limited to two binding structures which is single jersey and wevknit.

2. Literature review

2.1 Effect of moisture on skin

Moisture related skin damage occurs because too much moisture weakens the skins protective barrier. The outermost layer of the skin (stratum corneum) which serves as the protective layer, is usually slightly acidic and helps to keep out harmful bacteria and fungi. However, when the skin is exposed to moisture, especially with friction, it can break down and making it easier for infections to occur. Common culprits are Candida albicans (fungus) and Staphylococcus (bacteria). Frequent washing, especially with soap and water, can further strip away the skin's natural protection, leading to irritation and damage (Zulkowski 2012). Irritant contact dermatitis is a common skin condition caused by prolonged exposure to moisture and occlusion. When the skin is covered by absorbent products like diapers and sanitary pads, it can trap moisture, leading to irritation and inflammation. Many women experiences itching and burning in skin areas that is in contact with sanitary napkins during menstruation. Similarly, infants and young children often develop diaper rash due to prolonged moisture exposure (Ogawa-Fuse 2019). Urine is alkaline and can alter the skins pH by making it less acidic. This shift in pH and can increase the activity of enzymes, particularly in cases of faecal incontinence, leading to further skin breakdown and irritation (Zulkowski 2012). When stratum corneum is compromised by excessive hydration, harmful substances can penetrate the skin, triggering an inflammatory response (Ogawa-Fuse 2019).

Research indicates that factors such as sweating, body fluids, and the use of absorbent materials where moisture is trapped contribute to increased skin hydration, weakening the stratum corneum and making the skin more susceptible to irritation. Many studies have assessed the effects of moisture on skin integrity and found that maintaining a balanced hydration level is crucial for preventing irritant contact dermatitis. To reduce the risk of irritant contact dermatitis, it is important to use moisture vapor permeable materials and ensure proper hygiene. Strengthening the skin barrier can help the protection against irritation and maintain skin health (Ogawa-Fuse 2019).

2.1.1 Human sweat

The purpose of sweat is well known as to regulate the temperature of human body and prevent overheating. It is mainly made up of water and NaCl and the rest is a mixture of micronutrients (calcium, magnesium, iron and vitamins), metabolites (glucose, lactate, urea, bicarbonate etc.) and small amounts of organic compounds (cortisol) (Baker 2019). Human sweat has a pH ranging from 5 up to 7, while 5 is for lower sweat rates and 6.5 to 7 is for higher sweat rates (Salvo 2013). A study found that children have a more acidic sweat than adults with pH levels of 5.0-5.4 in children and 6.2 in adults. Sweat lactate was also higher in children. While age clearly affects sweat pH, no significant differences were found between adult's males and females in literature. More research is needed to clarify the effects of sex and race (Meyer, Laitano, Bar-Or, McDougall & Heigenhauser 2007).

There exist two different sweat glands on the skin: eccrine and apocrine. Apocrine glands do not have the function to regulate body temperature and are only operational during puberty (Salvo 2013). For many species, the apocrine glands create scent, primarily to produce pheromones (body odour) and for humans, this function is incomplete developed (Baker 2019). Apocrine gland's structure is alike hair follicles. Eccrine glands on the other hand are smaller, and the dimensions can vary from individuals. They are active from birth and its function is to produce sweat to regulate body temperature together with the skins capillary blood vessels when their skins temperature reaches over 32-34 °C (Salvo 2013).

2.2 Moisture transportation in textiles

Textiles with moisture transporting properties provide comfort to the wearer by quick evaporation of moisture and keeping the skin dry. Great moisture management ability in a fabric enhances body thermal comfort (Wang 2018). Moisture management is an important factor in modern clothing, ensuring that sweat is effectively moved away from the skin to the outer layer of the fabric. This prevents discomfort caused by trapped moisture, which can lead to overheating in warm weather or cooling in cold conditions. Too much moisture that can cause the fabric to be soaked in liquid can also make garments heavier, increase friction and cause skin irritation (Paul 2019).

Managing moisture on a fabric that is close to the skin can be through developing moisture transferring textiles, wicking, which can also be known as spontaneous uptake/transportation of liquid (Kim, Michielsen & DenHartog 2020). Wicking relies on capillary action. The pores between the fibres act as capillaries that draw liquid away from the skin. Two key factors that influence this process are capillary diameter and surface energy. Those with smaller capillaries diameters capillaries or higher surface energy promote better moisture transport (Paul 2019).

A common solution for moisture control is combining a hydrophilic and hydrophobic layer. The inner layer that repels moisture to keep the skin dry and an outer layer that absorbs and spreads it for faster evaporation. Several factors affect how well a fabric manages moisture including fibre type, fabric construction, thickness and chemical treatments. Compared to cotton, synthetic fibres are often preferred for activewear because they do not absorb as much moisture, keeping garments lighter and drying faster while maintaining their shape (Paul 2019).

2.2.1 Moisture wicking mechanism

Moisture can be transferred through textiles in both vapor and liquid form, as illustrated in figure 1. Moisture transportation refers to the controlled movement of water, both in vapor and liquid state, from the surface of the human skin through the textile materials to the surrounding environment (Gibson & Charmchi 1997).

2.2.1.1 Vapor state

In vapor state, moisture moves through textiles via four primary mechanisms, as described by Gibson & Charmchi (1997) and Wang (2018). First, diffusion allows water vapor to pass through the fabric due to differences in moisture concentration. Vapor molecules, being extremely small, navigate through the air gaps between fibres and yarns, helping moisture move from one side of the textile to the other (Gibson & Charmchi 1997). Second, surface adsorption and migration occur when water vapor adhere along the fibre surface. This is driven by surface energy, which causes moisture to cling to and travel across the material. Third, absorption and desorption take place men fibres take in moisture vapor and later release it. This dynamic process allows moisture to move in and out of the textile structure itself and impacting how wet or dry the fabric feels. Lastly, forced convection transports vapor away through air movement. When air passes over a damp fabric, it carries away moisture, controlling the rate of drying. This mechanism is influenced by factors such as fibre type, humidity and temperature which all affect how well a fabric manages moisture. Understanding these mechanisms is important in designing textiles with effective moisture control whether for comfort, performance or specialised applications (Wang 2018).

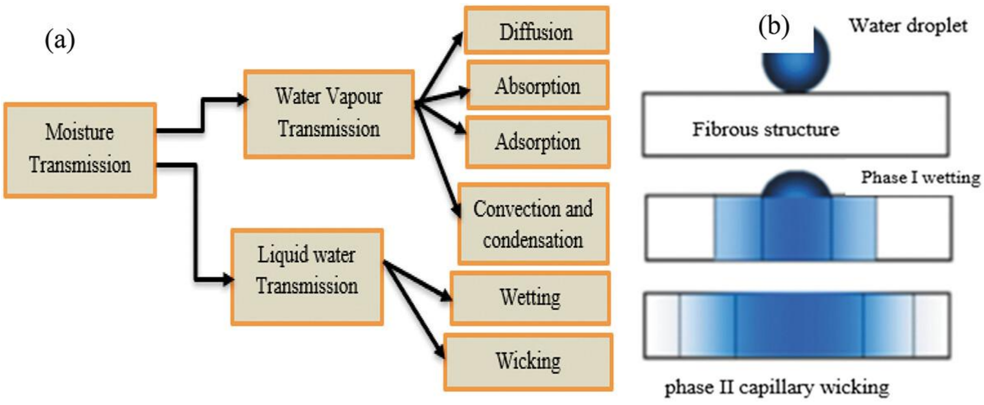


Figure 1. a) Moisture transfer mechanism and b) Liquid transport through fabrics (Image source: Yilma & Limeneh 2022)

2.2.1.2 Liquid state

In liquid state, moisture or liquid transfers through textiles via mechanism involving wetting and capillary condensation. The liquid form travel through the fabric in two different processes. Initially, the liquid start to wet the fabric in a process called wetting. The molecules of any liquid or moisture wet the fibre before transferring further to the amorphous regions of the fibre. The interaction of the cohesive forces within the liquid and the adhesive forces between the liquid of the fibres determines the wettability of the fibres. There is spontaneous wetting and forced wetting. Spontaneous wetting is in terms of thermodynamic equilibrium. Forced wetting increases the interface beyond the equilibrium with external hydrodynamic or mechanical forces. If a liquid does not firstly wet a fabric, then it does not travel through the fabric (Hang, Sun & Ye 2012; Wang 2018).

Once the textile is wetted, wicking follows, which is considered one of the most critical mechanisms for liquid moisture absorption and transport in textiles (Hauke & Moreau 2008). Wicking is driven by capillary forces, which come into play when a porous fabric makes contact with a liquid. The results of the capillary forces draw the liquid into the capillaries (pores) and the wicking ability maintain the capillary flow. When the spaces between the fibres are wetted by liquid, wicking occurs (Hauke & Moreau 2008; Wang 2018).

2.2.2 Factors affecting the wicking property

There are many factors affecting the moisture wicking property in a fabric. Factors such as fabric structure, fibre arrangement and shape and the capillary channels that exist within the material. All these factors play an important role in the moisture diffusion process in material (Gibson & Charmchi 1997; Wang 2018).

Moisture transport in textiles is influenced by both the fibre type and the fabric construction. Onofrei, Rocha and Catarino (2011) found that wicking ability is primarily influenced by the knitted structure, while the drying rate is largely determined by the fibre type, with construction playing a second role. Contrarily, Sampath and Senthilkumar (2009) emphasise the importance of fabric construction, identifying it as the second most significant factor in moisture management. They argue that knitted fabrics, owing to their larger pore sizes, allow better transmission of liquid compared to densely woven fabrics. Their findings also highlight that polyester fabric generally perform better in terms of moisture management than cellulosic fabrics. Additionally, they note that moisture management finishes can further improve the fabrics ability to retain and transport moisture. Treated fabrics are commonly assessed through parameters such as wetting, wicking and water absorbency (Sampath & Senthilkumar 2009).

Wettability, which affect how a liquid spreads over and enters the textile, is determined by the surface tension of both the material and the liquid. It depends on factors such as fabric, structure, area density and fibre orientation. The wicking process itself is driven by capillary action and is influenced by the cross-sectional shape of the fibres, pore tortuosity, yarn twist and yarn texture. The property of wicking is also highly affected by the hygroscopicity (moisture absorption capacity of fibres), as well as its hydrophilicity and hydrophobicity (Wang 2018). The processes of diffusion and wicking are also affected by the liquid's viscosity and surface tension. Higher viscosity or surface tension may lead to a lower transporting coefficient (Rajagopalan, Aneja & Marchal 2001). Hydrophilic fibres, which have high surface energy, absorb moisture more than hydrophobic ones. Fabrics with microfibres which contain many narrow capillaries are particularly effective at moisture transport. While absorbent materials can pull moisture into the fabric, they may also retain it, making the garment feel damp and uncomfortable. The most effective moisture wicking fabric is a balance by quickly moving sweat away while minimising water retention. This helps regulate body temperature, optimal performance and delay fatigue, which is an important feature for sportswear. However, materials that block moisture entirely can also trap heat, leading to discomfort during physical activity (Paul 2019).

Additionally, the geometric structure of the capillaries plays an important role. The size, shape, and alignment of the fibres determine the geometry of the void spaces or pores through which the liquid moves. However, due to the complexity of fabric structures, predicting pore arrangements is nearly impossible, and experimentally determining their detailed structure is highly challenging (Rajagopalan, Aneja & Marchal 2001). Other factors affecting the moisture transferring is also the environment such as temperature and humidity. Moisture transfer mechanism becomes more complicated when more than one layer of fabric is involved (Wang 2018).

The tiny spaces within individual yarns primarily drive liquid movement, while the larger gaps between yarns does not contribute much to spreading liquid over long distances. Research found that where yarns cross each other, they act like small reservoirs, distributing liquid evenly in all direction. This is important when comparing different knitting structures, as their design will influence how moisture moves through the fabric (Patil, Kane & Ramesh 2009). The tiny pores inside a material are not uniform, they come in different shapes and sizes, creating a complex network for transporting liquids. These pores can also change when the material interacts with fluids or heat. For example, some fibres, like cotton, may swell and the material can deform as it absorbs liquid. Since this affects how liquids travel, studying its internal structure, especially its pore size distribution may give understanding to how a material moves moisture (Pan & Gibson 2006)

2.3 Hydrophobicity & Hydrophilicity in textiles

Hydrophobicity can be described in terms of wetting behaviour, which is often quantified by measuring the static angle between a liquid droplet and a solid surface (textile). Several factors that influence the contact angle, including surface energy, surface roughness and surface cleanliness. A surface is considered hydrophilic when the contact angle is between 0° and 90°, meaning the liquid spread more easily across the surface. Surfaces with a contact angle between 90° and 180° are hydrophobic, indicating poor wetting. Surface roughness can significantly influence wetting behaviour. According to models like Wenzel and Cassie-Baxter, increasing roughness can improve both hydrophilic and hydrophobic properties. The Wenzel model addresses homogeneous rough surfaces where the liquid fully penetrates the surface texture. The Cassie-Baxter model applies to heterogenous surfaces where the liquid rests atop the surface (Bhusan & Jung 2011). On a hydrophobic surface, increased roughness can trap air beneath the droplet, reducing the contact area between the liquid and the fabric, and thereby increasing the contact angle. This effect can lead to superhydrophilicity where the contact angle exceeds 150°, and the liquid rolls off easily. In practice, surfaces often exhibit a combination of these two states and transitions between them can occur through evaporation of liquid or under external stimuli like pressure or vibrations (Bhusan & Jung 2011; Melki, Biguenet & Dupuis 2019).

In textile materials, the hydrophilicity or hydrophobicity of the fibres plays an important role in moisture management. Natural fibres such as cotton are inherently hydrophilic, as they have numerous bonding sites for water molecules. While this enables them to absorb moisture from the skin efficiently, it also means that moisture is often retained within the fibres, resulting in poor moisture transport and slow drying (Onofrei, Rocha & Catarino 2011). In contrast, synthetic fibres like polyester, polypropylene and polyamide are generally hydrophobic (Kadolph 2014). These materials absorb very little moisture but facilitate quick transfer and release of water, making them well suited for moisture wicking applications. For example, while cotton can absorb sweat effectively, it struggles to release it into the air. Synthetic materials, although less absorbent, have better overall moisture management properties due to their efficient moisture transport and quick drying (Öner, Atasağun, Okur, Beden, & Durur 2013). Among the commonly used hydrophobic fibres, polyester is known for low moisture absorption and excellent wicking, polypropylene for its lightweight and quick drying behaviour and polyamide for its durability and moderate moisture management (Kadolph 2014; Motlogelwa, 2018).

The heat and moisture transfer properties of a textile are directly related to the thermal and physiological comfort experienced by the wearer (Chen et al. 2021). Comfort can be achieved through fabric design, such as 3D knitted structures (spacer), commonly created from warp and weft knitted fabrics. These structures form air layers that promote ventilation, allowing heat and moisture to evaporate efficiently (Arumugam, Mishra, Militky & Salacova 2019).

To further improve moisture management, textiles can be engineered using finishing treatments. These may involve the application of chemical treatments or the design of multi-layer fabrics combining hydrophilic and hydrophobic layers. Such approaches aim to improve both absorption and release of moisture, enhancing wearer comfort (Prakash & Ramakrishnan 2019).

Studies on two-layer knit fabrics have shown that variations in structure can significantly impact moisture and thermal management. In a study by Yang, Yu, Chen and Zhang (2021), two-layer knits with mesh on one side demonstrated improved air permeability, drying rate and dynamic cooling effect was achieved, although they had lower wicking heights compared to symmetrical two-layer knits with trimmed structure (Yang et al. 2021). Similarly, Sadhna et al. (2024) developed a tri-layer knitted fabric using bamboo, polypropylene, hollow polyester and polyester staple fibres positioned on the face side, middle and reverse sides of the fabric. The study investigated how these materials influenced moisture management. The findings showed that the combination of bamboo on the outer layer, hollow polyester as the inner and middle layer provided superior moisture regulation, offering comfort and making them suitable for summer apparel and activewear. The use of hollow polyester yarn contributed to a larger wetting radius, faster moisture absorption, longer wetting times, shorter drying rates and quicker diffusion, all of which contributed to improved comfort properties (Sadhna et al 2024).

There is a common misconception that 100% cotton knitted fabrics provide the best thermal comfort due to its ability to absorb sweat quickly (Yilma & Limeneh 2022). While cotton does absorb moisture effectively, it retains wetness for a long time, which can lead to discomfort during prolonged use or physical activities. In contrast, fabrics that absorb moisture and dry quickly are generally more desirable. This balance may be achieved through chemical treatments, fibre blending or use of microfibres, all of which improve drying and moisture transport properties (Sampath & Senthilkumar 2009; Yilma & Limeneh 2022).

2.4 Fibre properties

The current fabric applied for DRYEs inner glove is made of a Tencel and polypropylene blend. The gloves moisture wicking concept is a single layer fabric, placing Tencel as the outer side to function as the absorbent side and polypropylene as the inner side to transfer sweat to the outer surface, keeping the hands dry. Tencel is the hydrophilic fibre, and polypropylene is the hydrophobic fibre in this case.

2.4.1 Tencel

Lyocell is a regenerated cellulose fibre made from wood pulp. It is comparable to rayon but is manufactured using a more environmentally friendly process. Tencel is the brand name for lyocell fibres produced by the Austrian company Lenzing AG (Tencel n.d.). Unlike other cellulose fibres such as viscose, lyocell is produced using a closed-loop process in which the solvent is recovered and reused in a cycle that recaptures the chemicals. This reduces harmful waste and emissions and requires less water and energy, making Tencel a more sustainable choice. Although lyocell does not decompose effectively in landfill conditions, a study by Royer, Greco, Kogler and Deheyn (2023), found that lyocell fabrics was completely broke down within one month in marine conditions. However, while often viewed as an environmentally friendly responsible material, it is important to note that lyocell is currently not recyclable through conventional textile recycling systems (Kadolph 2014).

Lyocell fibres are characterised by their soft, smooth texture and inherent hydrophilicity that often resembles cotton with high moisture regain (Bechthold & Pham 2019). Making it ideal for applications that are close to the skin such as activewear, underwear and apparel. Lyocell also possesses high tensile strength, including in wet conditions, which is valuable in applications requiring durability and stability under moist conditions. However, the fibre is not without limitations. One issue is its tendency to fibrillate, especially when exposed to repeated abrasion. This can lead to surface fuzziness, pilling or changes in in appearance over time. In response, cross-linked versions such as Tencel A-100 have been developed to significantly reduce fibrillation problems and improve surface resilience. From a chemical resistance view, lyocell is sensitive to acids, dilute alkalis and most organic solvents. As a cellulose fibre, it is also vulnerable to damage from mildew and certain insects, especially in humid or poor ventilated conditions (Kadolph 2014).

Tencel fabrics offer a blend of comfort and performance, supporting the growing use in home textiles and workwear. The fibres absorbency, colour depth and strength, both in dry and wet conditions, make it ideal for products like towels and absorbent wipes. The fibres eco-friendly production is a key factor in its market appeal (White 2001). Recent developments in fibre and yarn engineering also highlight the advantages of lyocell. Blending eco-friendly fibres like lyocell and bamboo into yarn have proven to improve moisture absorption and drying performance. In particular, the core yarn structure plays an important role in wicking behaviour, with the fibres cross-sectional shape and hygroscopicity being key abilities (Kim 2023).

2.4.2 Polypropylene

Polypropylene (PP) is a synthetic fibre classified as olefin, made from long chains of ethylene and propylene. It is characterised by a low density, excellent chemical and abrasion resistance and a non-absorbent nature. These properties make it suitable for producing lightweight yet highly durable materials at relatively low cost. Modern polypropylene can also be engineered with varying cross-sections, fibre diameters, crimp and lustre to meet specific performance requirements across different applications, giving it a more “natural” feel rather than synthetic (Kadolph 2014). One of the most defining properties of polypropylene is its high hydrophobicity. Due to the lack of polar groups in its polymer chains, it resists interaction with water and most chemicals with varying pHs. The fibres surface energy ranges between 28-30 mN/m and its moisture regain is less than 0.1% (Bechthold & Pham 2019). In sports and activewear, polypropylene is commonly used as a base layer material, since its low moisture retention ensures sweat is not absorb into the fabric, instead transported to the outer layer, promoting quick drying. The surface energy of polypropylene is quite similar to that of sweat, skin and even plant oils. This similarity supports the efficient movement of sweat across fibre surface. In addition to sportwear, polypropylene is also applied to hygiene products, such as disposable diapers, where polypropylene serves as the surface layer to maintain dryness and prevent fluid penetration (Bechthold & Pham 2019; Kadolph 2014).

Hydrophobic fibres like polypropylene are highly effective at moisture transportation, instead of absorbing sweat, the fibre likely allow the sweat to wick along the fibre surface and evaporate quickly. In contrast, hydrophilic fibres tend to retain moisture and are more suited for moisture storage (Sathish Babu, Senthil Kumar & Senthil Kumar 2020). Within knitted fabrics, the incorporation of functional fibres, such as polypropylene or polyester, can significantly influence wicking behaviour and drying time. Research has shown that fibre placement plays a key role, by positioning functional fibres closer to the skin improves moisture transport properties (Fangueiro, Filgueiras, Soutinho & Xie Meidi 2010).

2.5 Circular knitting

The fabric used in DRYEs current glove is produced using a circular knitting machine. The fabric is the cut, trimmed and sewn together to become a glove in later processes. Circular knitting is a method of creating fabric on a continuous tube using circular knitting machines. Instead of working back and forth in rows like flat knitting, circular knitting works in rounds, which produces seamless tube of fabric. This method is commonly used to make products like t-shirts. There are two different types of machines, usually categorised as single-bed (Single Jersey) and double-bed (Double Jersey) machines (Peterson 2013). Traditional circular weft knitting machines come with certain limitations. They typically require a large number of yarn feeders and cylinders, which contributes to high energy consumption during production. These machines are generally designed to produce fabrics with uniform structures, offering minimal flexibility for structural variation (Dong, Fang, Ding, Cong & Ma 2024)

In circular knitting, machine parameters such as yarn tension, loop length, machine speed and take-down force can be systematically adjusted to influence fabric structure and performance. These parameters are central to stitch formation and determine fabric properties such as dimensional stability and texture. Among these parameters, yarn tension plays a particularly critical role. It affects the interaction between yarn and knitting needles during loop formation, which directly influences stitch uniformity and structural consistency. Higher yarn tension has been found to increase needle displacement, which can lead to variation in stitch size and potentially compromise fabric structure (Duru, Candan & Mungan 2015). Yarn tension is also closely linked to loop length, making it an important factor in maintaining consistent fabric quality across production runs. Adjusting machine parameters must be approached with care, since inconsistencies may disrupt the knitting process and impact fabric quality (Dias & Lanarolle 2002). The structural implications of yarn tension are particularly seen in weft-knitted single jersey fabrics. Spirality, a common dimensional distortion in these fabrics, can be a result of too high yarn tension (Sarker et al. 2022). Sarker et al. (2022) found that these variables, when misaligned, led to pronounced spirality, highlighting the need for careful of production settings.

2.5.1 Single Jersey

DRYEs glove is knitted using a single jersey knit. Single jerseys are produced using single-bed machine. It is a weft-knitted fabric using one set of needles that produced fabric with distinct front and back sides. The front side typically resembles a V-shape while the back resembles U-shape. This structure is lightweight, stretchy (especially on the width direction) and has a smooth surface on the front and amore textured feel on the back (Peterson 2013; Fashionary 2024).

2.5.2 Swiss Wevknit

Wevknit is a binding originally developed from a weave-like structure. In the 1940s, it gained attention by the Swiss manufacturer DUBIED, who launched a circular knitting machine specifically designed for such structures. This led to the development of *Wevknit*, a name derived from “weave” and “knit”. It was recognised for its combination of woven appearance, flexibility and excellent dimensional stability. The technical face side of the fabric resembles a piqué texture and the most common machine gauges ranging from E18 to E24 on a double-bed machine. This fabric structure also produces different front and back sides. This structure is also known by other names, such as *Double piqué* and *Overnit* (Bengtsson 1995).

2.6 Heat setting

Heat setting is a thermal process used for heat sensitive fibres to stabilize yarns or fabrics. The main purpose of heat setting is to improve dimensional stability, appearance and performance by locking in their shape and structure. Heat setting not only stabilises dimensions but also help set yarn twist, define weave or knit crimp and improve wrinkle resistance. During heat setting, the fabric is placed in a stenter frame and placed into a heated oven, where it is heated to a specific temperature known as the glass transition temperature (T_g), a point where the molecular chains within the fibre become mobile enough to relieve internal stress (Kadolph 2014; Morris & Murray 2022). While the fabric is held in a controlled position, often stretched or fixed in desired shape, the heat allows the molecules to rearrange. In this setup, temperature and exposure time are precisely regulated according to the fibre's properties and any finishes (if applied). Once cooled, the new fabric becomes permanent, and the material remains stable when exposed to temperature below the one used in the heat setting process (Kadolph 2014). Heat setting causes some changes in the properties of polypropylene yarn. It reduces strength, stiffness, bending resistance, crimp contraction and shrinkage. However, it increases the yarns linear density. These changes improve the yarns' ability to bounce back (resiliency), which leads to better appearance and durability (Sarkeshick, Tavanai, Zarrebini, & Morshed 2009).

2.7 Sustainability aspects

Sustainability involves a balanced consideration of environmental, social and economic factors. According to the United Nations, sustainable development is defined as "meeting the needs of the present without compromising the ability of future generations to meet their own needs" (United Nations n.d.). In the context of textile development, it is essential to evaluate how materials, production methods and end-use impact natural resources, human well-being and economic viability. This section outlines the key sustainability aspects relevant to the application of the inner gloves.

2.7.1 Environmental sustainability

Tencel is widely regarded as one of the most sustainable fibres, primarily due to its environmentally responsible closed-loop manufacturing systems. Approximately 99.5% of the solvent used is recovered, purified and recycled back into the process. The solvent is both non-toxic and non-corrosive, and the resulting effluent is non-hazardous (Fletcher 2014). Despite its resource efficient nature, the process is energy-intensive, and concerns remain about its end-of-life stage, as Tencel is not recyclable and decomposes very slowly in landfill (Kadolph 2014).

Using polypropylene in textiles raises several environmental concerns, especially related to pollution and long-term ecological damage. Polypropylene is a synthetic plastic and like many synthetic fibres, it sheds tiny plastic particles called microfibres during washing. These microfibres are a type of microplastic that do not break down naturally. Instead, they stay in the environment, build up oceans and soil and can harm wildlife and marine ecosystems (Priyadarshini, Jagatee, Das A., Das P. & Behera 2024). Studies have found that microplastics from textiles, including those made of polypropylene are now found almost everywhere, in water, soil and food. These small particles can also carry harmful chemicals, which may further increase their environmental impact. When animals accidently eat microplastics, it can affect their health and the balance of natural systems (Thompson et al. 2024).

The process of making polypropylene in textiles also puts pressure on the environment. It uses a lot of water and energy, releases carbon dioxide and can cause pollution through the chemicals used during production. On top of that, if polypropylene is disposed incorrectly, it takes hundreds of years to break down in landfills or in the natural environment (Uddin 2022).

The knitting process is energy dependent and contributes to environmental impacts through energy consumption, solid waste generation and the release of dust and noise pollution. During fibre spinning and knitting, lubricants and oils are applied to protect fibres from mechanical stress. However, these substances are typically removed during fabric washing prior to further processing, creating waste streams that are often challenging to treat due to their low biodegradability (Fletcher 2014).

A major technical barrier in textile recycling today is the diversity of fibre types and the widespread use of blended materials. These factors complicate sorting and reduce the efficiency of recovery processes. As a result, the quality of recovered fibres often declines, a process known as downcycling, limiting the commercial value and potential applications of recycled textiles (Anjimoon, Gurnani, Khan, Paul & Al-Jawahry 2024)

2.7.2 Social sustainability

Atopic dermatitis (hand eczema) has significant challenge to social sustainability particularly in terms of occupational health, fair access to safe working conditions and the long-term well-being of the workforce. The condition is especially prevalent among healthcare workers, where it contributes to increased absenteeism, reduced work capacity and by extension strain on already overburdened health systems. During the COVID-19 pandemic, intensified hygiene protocols led to a rise of hand eczema cases among healthcare staff, highlighting the vulnerability of essential workers and the urgent need for targeted preventive strategies (Symanzik et al. 2022)

To mitigate these impacts, integrated care models involving multidisciplinary collaborations have been proposed. These approaches not only aim to improve clinical outcomes but also seek to sustain patient engagement in the labour force, thereby reducing both direct healthcare costs and indirect losses in productivity (Van Gils et al. 2009).

The societal burden of hand eczema is further reflected in its high incidence among healthcare professionals, where it frequently attributed to occupational exposure such as repeated contact with irritants and triggers (Chiriac et al. 2016; Chiriac et al. 2020). Beyond physical symptoms, hand eczema can severely impact quality of life, limiting individuals daily functioning and contributing to psychological distress. Long et al. (2022), claims in their study that hand eczema has been associated among clients to develop anxiety and depression. As such, addressing hand eczema is not solely a matter of personal health, it is a prerequisite for fostering resilient, healthy communities where individuals can participate fully and sustainability (Qu et al. 2024).

2.7.3 Economical sustainability

As mentioned, occupational exposure is a major contributor to hand eczema, particularly in sectors such as healthcare, metalworking and farming. In the Swedish healthcare, hand eczema affects 21% of hospital employees (Hamnerius et al 2018), markedly higher than the general population (10%) (Arbetsmiljöverket 2012), primarily due to frequent hand washing, glove use and exposure to disinfectants. However, the latter did not show a dose-dependent relationship with the condition (Hamnerius et al. 2018)

In Norway, the lifetime prevalence of hand eczema in the general population is 11.3% with 4.8% reporting work-related cases. Health and social care, cleaning and farming were identified as high-risk profession, with cleaning detergents serving as a major triggering factor (Vindenes et al. 2017). Similarly, a study of metalworker trainees found that 23% showed signs of hand eczema, with risk factors including atopic disposition, exposure to mechanical irritants and inadequate skin recovery time (Bernt, Hinnen, Iliev & Elsner 2000).

The economic consequences of occupational hand eczema are substantial. The condition can lead to absenteeism, job changes, and reduced quality of life (Armstrong et al. 2022; Clemmensen, Randbøll, Ryborg, Ebbehøj & Agner 2015). In Denmark, skin conditions like hand eczema constitute a significant proportion of recognised occupation diseases, reflecting the economic burden. Encouragingly, preventive strategies such as evidence-based training for hospital cleaners have been effective in reducing incidence rates, highlighting the potential for targeted interventions to lessen both health-related and economic cost (Clemmensen et al. 2015).

In summary, polypropylene in textile poses serious environmental challenges, these includes microplastic pollution, high resource use during production, and long-lasting waste. Because of this, there is a growing need to explore sustainable materials and improve waste management in the textile industry. The management of hand eczema is linked to social sustainability through its effect on workforce health, economic productivity and overall quality of life. Addressing this condition through targeted interventions can enhance both individuals' well-being and societal functioning. Occupational hand eczema not only poses a significant health concern but also carries notable economic implications such as reduced productivity, emphasising the need for effective preventive measures across high-risk industries.

3. METHODOLOGY

3.1 RESEARCH DESIGN

This project uses a quantitative research approach to systematically analyse the impact of the moisture transportation properties of blended Tencel-polypropylene knitted fabrics used for inner gloves. The company did not set any prior requirements for this research; however, the only goal for the company is to "optimise" their current fabric by exploring different fibre ratios (distribution of fibre type) and textile structures. The goal is to determine if they should keep their current fabric used in the inner gloves or apply one of the samples used in this study. Therefore, since no specifications exist or any specific requirement is required, this study does not use any hypothetical theories. Following an inductive, a bottom-up logic which usually begins with empirical observations, allowing patterns to appear and guiding the development of potential conclusions. These conclusions may eventually contribute to a theory that explains the observed phenomena. Rather than testing predefined hypothesis, this research seeks to identify trends and relationships within the collected data, allowing insights to appear through statistical analysis (Säfsten & Gustavsson 2023). To support this process, the study relies on primarily quantitative data from test results and measurements to compare samples. The primary data source consists of test results of material performance in terms of moisture transport, performed under controlled conditions. The tests were chosen to measure the spreading of liquid, time of spreading and moisture wicking capacity using standardised test methods to ensure consistency and reliability. The test results analysed using descriptive and statistical method to identify relationships. Additionally, secondary data from literature review will provide further context and validation. For the literature review, Primo and Scopus were primarily used search engines and only peer reviewed articles and studies were used as reference.

3.2 Material

Fabric samples were produced using two different circular knitting machines, one for single jersey and another for wevknit. For this project, a total of 10 samples will undergo testing and comparison, with one sample serving as the original reference fabric (REF) provided by the company. The reference fabric (REF) uses the same polypropylene but a thinner Tencel yarn count. From here on, fabric side containing most Tencel will be referred to face side and fabric side containing most polypropylene will be referred to skin side (see figure 9). Yarns used for knitting in this study can be seen in table 1.

Table 1. Specification of yarns used in this study

Yarn	
Tencel	Ne 30/1 A-100, White
Polypropylene	Nm 1/50 Polycon, Schoeller, Black

3.2.1 Single Jersey

Three samples were produced in single jersey (table 3). The single jersey knits were produced using circular knitting machine manufactured by Mayer & Cie with gauge E12. Single jersey samples are abbreviated as “SJ”. Further details about knitting parameters can be found in Appendix 1. Sample SJ7 and SJ8 have the same yarn feeding positioning, placing Tencel on the front, while SJ9 and reference fabric have the opposite yarn feeding with Tencel positioned on the back of the fabric.

3.2.1.1 Reference fabric

The reference fabric provided by the company is a single jersey. It was produced using a circular knitting machine with gauge E14 with the yarn count Nm 1/60 (Tencel) and Nm 1/50 (polypropylene), see table 2. The Tencel is positioned in the back of the fabric.

Table 2. Technical specification of the reference fabric

Reference fabric	
Tencel	Nm 1/60, A-100, White
Polypropylene	Nm 1/50 Polycon, Schoeller, Black
Machine	Terrot S3P 248
Gauge	E14

3.2.2 Swiss wevknit

Since one of the goals of this project was to determine the optimal percentage distribution of Tencel and polypropylene, this binding was chosen due its higher flexibility in fibre ratio distribution. This structure additionally allows the two fibre types to be positioned on opposite sides, creating a hydrophobic and hydrophilic surface. To further explore the different percentage composition of this material, samples of different fibre distribution in Swiss wevknit structure was also produced. This binding differs from the reference fabric. A total of six Swiss wevknit samples were produced using a circular knitting machine manufactured by Mayer & Cie with gauge E20, see table 3. Swiss wevknit samples are abbreviated as "SW". Samples SW1, SW2 and SW3 have the same yarn feeding positioning, placing Tencel on the front. Samples SW4 and SW5 have the opposite yarn feeding positioning, placing Tencel on the back. These samples have distinct hydrophobic and hydrophilic sides. Sample SW6 differ from the rest of the samples and does not have hydrophobic or hydrophilic sides, the yarns are blended throughout the fabric, and the yarns are present at both sides. Further details about machine settings can be found in Appendix 2.

Table 3. Summary of all samples including percentage of each yarn type and machine settings

Material composition (%) and machine parameters			
Sample ID	**Tencel**	**Polypropylene**	**Parameters**
SW1	74.8	25.2	Yarn tension: 4 Loop length: 10
SW2	77.2	22.8	Yarn tension: 2 Loop length: 10
SW3	78.11	21.89	Yarn tension: 2 Loop length: T-5, PP- 10
SW4	26.2	73.8	Yarn tension: 2 Loop length: 10
SW5	24.3	75.7	Yarn tension: 4 Loop length: 10
SW6	50	50	Yarn tension: 4 Loop length: 10
SJ7	48.3	51.7	Yarn tension: T-3.4, PP-0.9 Loop length: 19
SJ8	48.5	51.5	Yarn tension: 3.4 Loop length: 19
SJ9	49.4	50.6	Yarn tension: 3.4 Loop length: 19
REF	45	55	No data available

To calculate the percentagewise of material distribution on each sample, yarn cones were measured with a sensitive scale before and after knitting to calculate the yarn consumption for each yarn type for each fabric sample. The percentage-wise composition was calculated using formula:

Equation 1. Formula to calculate material distribution of knitted fabrics

$$Yarn\ percentage\ (\%) = \left(\frac{C_{yarn}}{C_{total}}\right) \times 100$$

Where C_{yarn} is the mass consumption of one yarn type in grams (g) and C_{total} is the total mass consumption of both yarns.

3.2.3 FABRICATION OF SWEAT SOLUTION

Artificial sweat will be prepared as it is the primary liquid the inner glove will be exposed to. Both an alkaline and acidic sweat solution will be fabricated according to standard ISO 105-E04:2013. Preparing and mixing the sweat solutions are required to be freshly made and are intended to be applied for the vertical wicking tests. Recipe for both solutions can be seen in table 3 and 4.

Table 4. Recipe for alkaline sweat solution

Alkaline solution	
Substance	**Amount**
Grade 3 water complying with ISO 3696	1 litre
l-histidine monohydrochloride monohydrate ($C_6H_9O_2N_3 \cdot HCl \cdot H_2O$)	0.5g
Sodium chloride (NaCl)	5g
Disodium hydrogen orthophosphate dodecahydrate ($Na_2HPO_4 \cdot 12H_2O$)	5g
The solution was brought to pH 8 (±0,2) with 0,1 mol/l sodium hydroxide solution.	

Table 5. Recipe for acidic sweat solution

Acidic solution	
Substance	**Amount**
Grade 3 water complying with ISO 3696	1 litre
l-histidine monohydrochloride monohydrate ($C_6H_9O_2N_3 \cdot HCl \cdot H_2O$)	0.5g
Sodium chloride (NaCl)	5g
Sodium dihydrogen orthophosphate dihydrate ($NaH_2PO_4 \cdot 2H_2O$)	5g
The solution was brought to pH 5,5 (±0,2) with 0,1 mol/l sodium hydroxide solution.	

0.1 mol/litre sodium hydroxide was mixed with deionized water until evenly distributed. 0.4 g sodium hydroxide was mixed with 1 litre deionised water.

3.3 TEST METHODS

Testing was performed to analyse and evaluate the performance of each fabric including the reference fabric. A total of three tests were conducted, horizontal wicking, vertical wicking and air permeability. All samples were washed according to SS-EN ISO 6330 standard, using a detergent without optical brightening agent in 60°C with SMS6N washing program (normal). The detergent dosage of 20 g was used for 2 kg of fabric. Washing machine is manufactured by Electrolux, model Wascator FOM71. After washing completed, the fabrics were air dried by hanging. Prior testing, all specimens were conditioned for at least 24h in accordance with ISO 139, under standard conditions (65± % relative humidity and a temperature of 20 ± 2 °C). A summary of test methods including samples are illustrated in table 6.

3.3.1 HORIZONTAL WICKING

The horizontal wicking is measured using Wickview by James Heal. This machine is an advanced laboratory instrument designed to analyse the moisture management of textiles. It provides real-time visualization of liquid movement through fabrics, allowing for precise data collection. Its automated data processing generates quantitative results such as spreading speed, direction and area coverage. This test is based on the AATCC 195 standard.

During testing, the specimen is placed horizontally with the skin side facing upward (figure 4 & 5). A precise automated droplet dispenser applies 0.2 ml of deionised water on the centre of the skin side of the specimen. The test duration is 2 min/specimen. A high-resolution infrared camera continuously records the moisture movement across both surfaces (skin and face) throughout the test (figure 2 & 3).

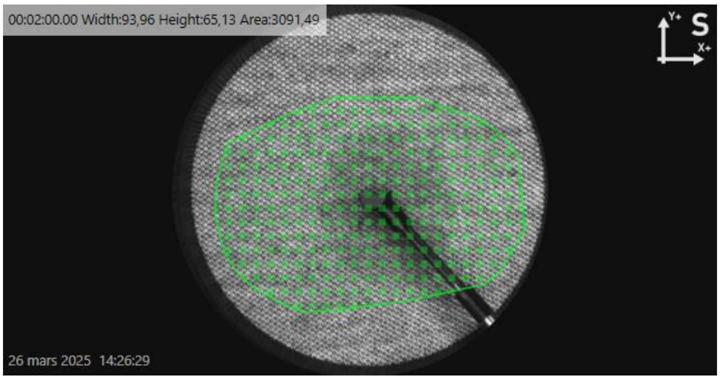


Figure 2. Capture of Wickview instrument applying water on skin side

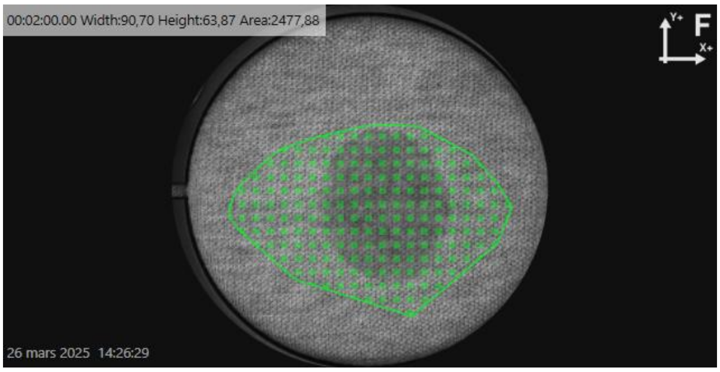


Figure 3. Capture of Wickview instrument measuring wetted area on face side

Each specimen measured to 15x15 cm, and ten specimens were prepared for each fabric sample. A total of 10 tests was performed per fabric sample. The specimen was clamped onto a cassette, aligned according to the wale and course of the knitted structures. The following parameters were collected, wetting time, relative absorption rate, wetted diameter and wicked area. Wetting time measures the time in which moisture is detected on the opposite side of liquid application. Relative absorption rate is the difference of wetted area in percent between the skin and face side after 120 s. Max wetted diameter measures in millimetres of the longest diameter under any time during the test period. Wicking area measures the widest moisture spread on the fabric in millimetres squared. All tests include spreading of skin and face side.

3.3.1.1 Modified wicking test – Liquid application on face side

While the standard Wickview protocol involves applying liquid to fabrics skin side to replicate sweat production and transport moisture away from the body, this configuration does not fully represent the real-life condition experienced by inner gloves used beneath impermeable protective glove. In such enclosed environments, the accumulation of moisture, whether from sweat vapor condensation, limited ventilation or humidity, can result in the outer (face) surface of the inner glove becoming damp. To more accurately simulate this context, a modified testing approach was implemented, whereas the fabric samples were rotated such that the face side was oriented toward the liquid source (see figure 6 & 7). Basically, simulating fluid which is trapped inside the microclimate entering from the outer side. Measures fabrics ability to retain and manage liquid without rewetting the skin. In this modified test, wetting time and relative absorption rate parameters was collected to evaluate the retention.

Only selected samples (SW1, SW4, SW6, SJ9 and reference fabric) were tested in this reversed configuration, based in their relevance. Samples SW1 was chosen due to its higher Tencel content and SW4 due to its higher polypropylene content. Sample SW6 has a more unique distribution of the fibres in comparison to the rest of the fabric samples, since Tencel and polypropylene are present both on the face and skin side and either of the sides can be chosen to be skin or face based on their performance. Fabric sample SJ9 and the reference fabric was also included in this reversed setup. SJ9 have a composition that resembles the reference fabric and for that reason both were included to enable comparative analysis.

This reversed configuration enables the evaluation of the fabrics wicking behaviour, assessing whether moisture can be absorbed and transported inward (towards the skin) when applied from the outer side. Understanding this reversed flow is particularly relevant in scenarios where sweat cannot evaporate efficiently due to the isolated and sealed environment of protective gloves but also facilitating in assessing the understanding of the wicking performance of the fabrics capacity to maintain skin dryness, regardless of moisture entry point. Test parameters remained consistent with the AATCC 195 standard to ensure reliable comparison between the standard and modified tests. Basically, the standard and modified tests are two sides of the same coin: release vs. retention. Together, by comparing both, fabrics that wick outward quickly while resisting inward wetting provide the best comfort in isolated glove environments.

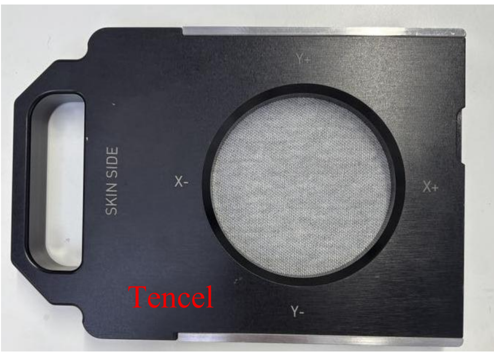


Figure 5. Tencel positioned on skin side of the cassette (standard test)

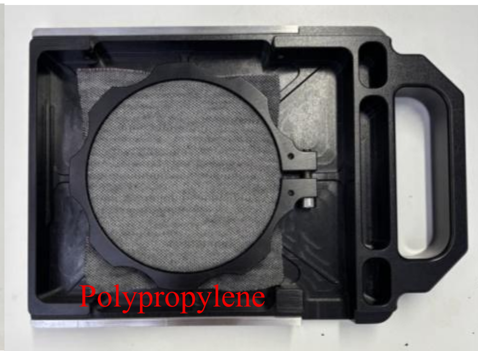


Figure 4. Polypropylene positioned on back side of the cassette (standard test)

Figure 7. Polypropylene positioned on skin side of the cassette (modified test)

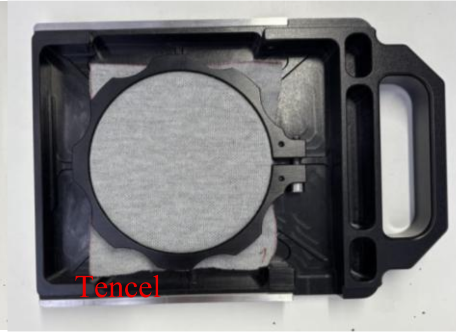


Figure 6. Tencel positioned on face side of the cassette (modified test)

3.3.2 Vertical Wicking

This study aims to investigate whether there is a difference between artificial sweat and deionised water in terms of moisture transport properties. The horizontal wicking instrument by James Heal were not compatible with using artificial sweat solutions. Therefore, vertical wicking test method was conducted to measure the influence of moisture transport using deionised water, acidic- and alkaline sweat solutions for comparisons. Horizontal wicking was chosen as the primary test method due to its controlled liquid application, real-time visualisation and better representation of the isolated glove environment. Since this method could only be conducted with water; vertical wicking was applied s a secondary method to allow comparative testing with different sweat solutions.

The vertical wicking test was conducted to evaluate the capillary transport of liquid through knitted samples in the vertical direction (figure 8), but also to determine if solutions with different pH could affect moisture transportation properties. This method is based on the AATCC TM197-2022 standard, which measures the distance a liquid travel vertically, against gravity, through a fabric over a specified period. In the standard procedure, deionised water is used as the test liquid. However, to better simulate the real-life conditions, this study employed two modified test solutions, an acidic artificial sweat (pH ≈ 5.5) and an alkaline artificial sweat (pH ≈ 8), formulated according to ISO 105-E04:2013 standard (see table 4 and 5). These solutions more accurately represent the range of sweat pH encountered during prolonged glove wear. This modified approach allowed for the assessment of moisture transport behaviour under physiologically relevant conditions, enabling comparison between different material compositions and knitting structures in response to water and sweat with varying pH levels.

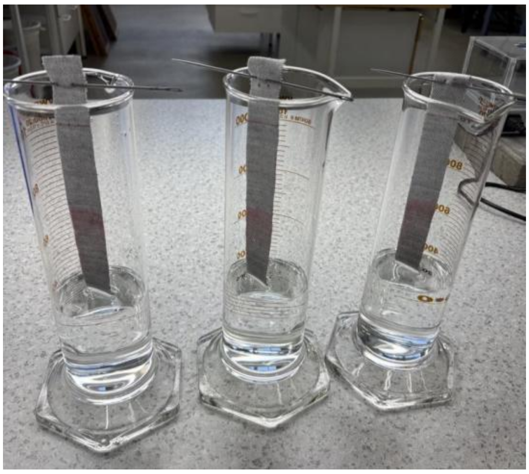


Figure 8. Procedure of vertical wicking test

Rectangular fabric specimens with dimensions 25x200 mm were cut, aligning the edges with the wale and course directions of the knitted structures. A water-soluble ink mark was placed 20 mm from the bottom edge and another 150 mm. A supporting pin was inserted 20 mm from the top of each specimen. Each specimen was suspended vertically with its lower edge immersed (approximately 1mm) in a beaker containing 400 ml of the test solution (figure 8). The time taken for the liquid to travel to the 20 mm mark was recorded, this measures the short-period wicking rate. The maximum height of the liquid uptake was measured after 30 min; this measured the long-period wicking rate. If the liquid reaches the 150 mm mark before 30 min, the test was stopped, and the time was recorded for the liquid to reach the mark. Separate tests were conducted using each of the three liquids, with three specimens/fabric type and solution to ensure reliability accordance to standard. The vertical wicking rate (W) was calculated using formula:

Equation 2. Formula to calculate the wicking rate according to AATCC TM197-2022

$$d/t = W$$

Where d represents the wicking distance in millimetres (mm) and t denotes the time taken to reach that distance in seconds (s). The wicking rate W is expressed in millimetres per seconds (mm/s).

The short-period wicking rate indicates how quickly the fabric begins to absorb and transport moisture to the point of contact. A high short-period wicking rate is important for quickly drawing sweat away from the skin, which contributes to immediate dryness. The long-period wicking rate indicates the fabrics ability to sustain moisture over time. A high long-period wicking rate suggests that the fabric can continuously manage moisture, which is important for prolonged glove wear. Together, these two rates provide comprehensive picture of the fabric wicking performance. The short period reflects how well the fabrics responds to sudden moisture exposure, while the long-period wicking rates shows how effectively it manages ongoing perspiration.

3.3.2.1 Surface tension

According to AATCC TM197-2022 (vertical wicking) standard, if any other liquid other than water is used for testing, its surface tension must be determined. Therefore, the surface tension of deionised water as well as artificial acidic and alkaline sweat solutions was measured using an Attension Theta Lite Optical Tensiometer by Biolin Scientific based on the pendant drop method. Each solution was measured 3 times at room temperature. The surface tension values were calculated by analysing the shape of the pendant droplet formed at the tip of the syringe, using the instruments built in image analysis software. The analysis was performed using the Young Laplace mode, with a droplet output size of 5000-6000 µl.

3.3.3 AIR PERMEABILITY

The air permeability of the knitted samples was evaluated in accordance with the standard SS-EN ISO 9237. This test method determines the rate of airflow passing through an area of fabric under a prescribed air pressure differential. The measurements were carried out using a Textest FX3300 Air Permeability Tester. A test area of 20 cm^2 was used and a pressure drop of 100 Pa was applied to the fabric as recommended for lightweight to medium-weight textiles. Each fabric variant was tested three times at different areas of the fabric, and the results were recorded in mm/s. The average values were used for comparison and further analysis. All samples were included in this test.

This test was conducted to gain more insight into how "breathable" a fabric is. Three different machines with different gauges (E12, E14, E20), was used to produce the samples in this study and the results of the fabric dense was varying. The lighter the fabric, the faster it dries but also does not store much moisture and vice versa.

Table 6. Summary of all test methods including the samples applied for each test

Test methods	Measurements	Fabric samples included
Horizontal wicking	- Wetting time (standard & modified) - Relative absorption rate (standard & modified) - Max wetted diameter (standard) - Wicking area (standard)	All non-heat setted samples
		Heat setted – SW1, SW4, SW6, SJ9, REF
Vertical wicking	- Short-period wicking rate - Long-period wicking rate	All non-heat setted samples
		Heat setted – SW1, SW4, SW6, SJ9, REF
Surface tension	- Alkaline solution - Acidic solution - Deionised water	None
Air permeability	- Airflow	All non-heat setted samples
		Heat setted – SW1, SW4, SW6, SJ9, REF

3.4 Finishing treatment

The reference fabric provided by the company had been heat set prior to testing. To enable a comparison and assess whether heat setting would have a significant impact on moisture wicking properties, a selection of four samples (SW1, SW4, SW6, SJ9) was also heat set. Each fabric was cut to 35x43 cm to fit into the stenter frame and treated at 120 °C for 160 s, which is the same parameters as the reference sample. Heat setting was performed using a Labcoater type LTE-S, manufactured by Mathis AG. This process was included to account for potential changes in fibre alignment, fabric structure or dimensional stability, all of which can influence moisture transport behaviour. "H" is included in the end of each heat setted sample ID for better identification.

Table 7. Summary of non-heat setted samples and heat setted samples

Non-heat setted samples	Heat setted samples
- SW1 - SW2 - SW3 - SW4 - SW5 - SW6 - SJ7 - SJ8 - SJ9	- SW1(H) - SW4(H) - SW6(H) - SJ9(H) - REF

3.5 Statistical analysis method

The collected data were analysed using Microsoft Excel. Descriptive statistics, including arithmetic mean values, standard deviations (SD) and coefficient of variation (CV) in percent were calculated on all measured tests to summarise the data. To determine statistically significant differences between groups, two-way analysis of variance (ANOVA) was applied where suited. Visuals were created using Excel to support the interpretation of data.

4. Concept development and design process

The development of the inner glove concept was initiated by DRYE AB, a Swedish company and was adapted to fit in the academic research context. The project began by identifying a real-world problem, professionals who wear protective gloves for extended periods often suffer from sweaty hands, leading to discomfort, hygiene issues and skin irritations. A literature review was conducted to build a foundational understanding of the research area. Applying design thinking, the problem was reframed, not simply as sweaty hands, but as the need for improved moisture management within gloves. The concept focused on a single layer with distinct hydrophilic and hydrophobic sides. A hydrophobic polypropylene layer to transport moisture away from the skin and a hydrophilic Tencel layer to absorb it, as illustrated in figure 9.

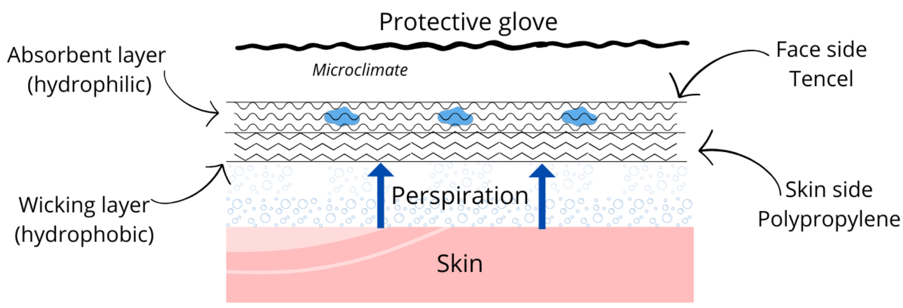


Figure 9 Illustration of fabric concept of hydrophobic and hydrophilic sides, including the positioning of yarn type

The focus in the beginning of the process was being placed on material distribution and knitting structures as the two main levers for moisture control. However, due to time constraints and yarn availability, the same polypropylene yarn as in the reference glove was used, while the Tencel yarn had to be replaced with a thicker variant. User testing was excluded from the scope, instead the study relies exclusively on fabric level quantitative testing.

With the problem and design direction defined, various textile structures with different material compositions were explored to improve moisture transport. A total of nine fabric sample was developed using different fabric combinations of Tencel and polypropylene. Together with a knitting technician, single jersey and Swiss wevknit structures were selected for their ability to form distinct hydrophobic and hydrophilic layers. Two different circular knitting machines were employed, a single-bed machine for single jersey and a double-bed machine for wevknit.

A major challenge was the limited yarn selection. The constraint of using only the available yarns restricted the ability to tune material distribution across the samples, especially with only two knit structures available.

In total, ten samples, including the reference fabric from the company, were tested. The fabric prototypes were evaluated through quantitative lab tests, focusing on moisture management properties and air permeability. The goal was to compare the performance of each sample and identify the most effective structure. Since sweat is the primary liquid encountered in glove use, tests were performed using both sweat solutions and water to investigate any performance differences. One of the main challenges was interpreting results across different testing methods.

5. RESULTS

The following section presents all the test results, including horizontal wicking (with liquid application on skin and face sides), vertical wicking (also surface tension measurements of the tested liquids) and air permeability tests. Beginning with the fabrics produced during circular knitting labs, followed by the test results of non-heat set fabrics, and concluding with test results of heat set fabrics.

5.1 FABRICS - CIRCULAR KNITTING

Microscopic pictures were captured of the knitted structures to better view the samples and their differences, placement of the yarns and loop geometry. Even though the design was to have distinct hydrophobic and hydrophilic surfaces, the results show that it was not successful for all samples. Some of the samples shows loops of the opposite yarn present on the other sides of the fabrics.

5.1.1 WEVKNIT

A total of 6 wevknits were produced using different machine parameters and varying material distribution, as seen previously in table 3. Samples SW1, SW2 and SW3 have approximately 75 wt% Tencel and 25 wt% polypropylene as seen in figure 10 where the white yarn (Tencel) is more present on the skin side, and partly on the face side. The difference here are the machine settings used during knitting. Samples SW4 and SW5 contain approximately 25 wt% Tencel and 75 wt% polypropylene and was knitted with an opposite yarn feeding positioning as well as different machine parameters. The differences of the yarn positioning can be seen in figure 10.

This study also aimed to explore 50/50 wt% material distribution throughout the fabric. However, this structure did not allow the yarn types to position on opposite sides when knitting 50/50 wt%. Therefore, sample SW6 features an even distribution of both yarn types on both sides, creating a blended fabric. Microscopic images of all wevknit structures and its differences can be found in appendix 3.

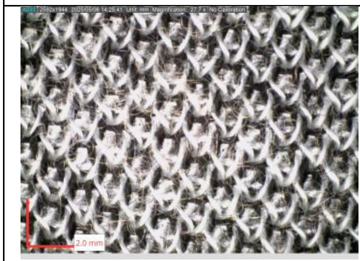
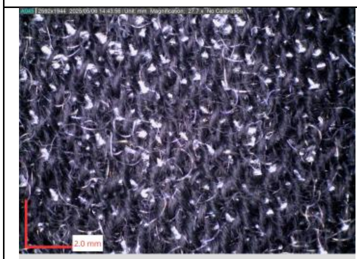
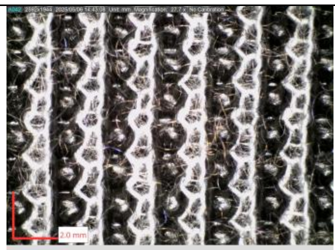
Swiss wevknit	
Skin side	**Face side**
 SW1	 SW1
 SW4	 SW4
 SW6	 SW6

Figure 10. Fabric structures of Swiss wevknit on the skin side and face side

5.1.2 *SINGLE JERSEY*

Achieving a yarn distribution of Tencel and polypropylene with more than a 1% difference between the samples proved challenging, in a single jersey structure. The limitation lies in the single jersey structure itself, which does not allow for a significant variation in fibre percentages using yarns of the same thickness. To alter the fibre distribution in a single jersey, yarns of different thicknesses are required. After three attempts to modify the distribution, despite adjustments to machines settings, the effort was to discontinue due to the lack of success. In the final samples, SJ7 and SJ8 have Tencel positioned on the front side, while SJ9 and reference fabric (REF) have it on the back side. The reference fabric was produced with a machine gauge E14 and the knitting loops are slightly tighter and smaller in comparison to SJ9. Microscopic images of single jersey structures and its differences can be seen on figure 11 and in appendix 3.

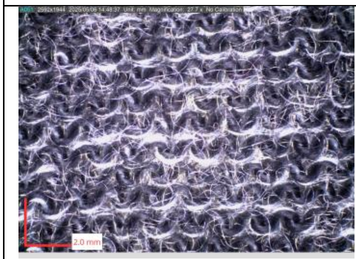
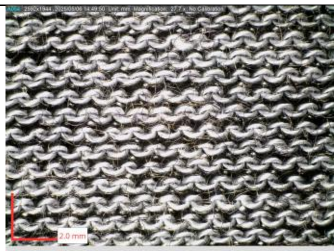
Single Jersey	
Skin side	**Face side**
 SJ8	 SJ8
 SJ9	 SJ9
 REF	 REF

Figure 11. Fabric structure of Single jersey on the skin side and face side

5.1.3 Domestic washing

After washing the samples, there were a notable difference on the fabrics surface, which can have an influence on the moisture transportation properties during testing. The fibres of the yarn had a more hairiness and fuzziness when observing with the eye as well as feeling of the hand. It was more prominent on SW4 and SW5, the samples which had higher content of polypropylene. Therefore, images were taken to visualise the before and after washing (figures 12 & 13). Only skin side was captured due to it being the side of moisture entry point. Images of all fabric surface images can be found in appendix 4.

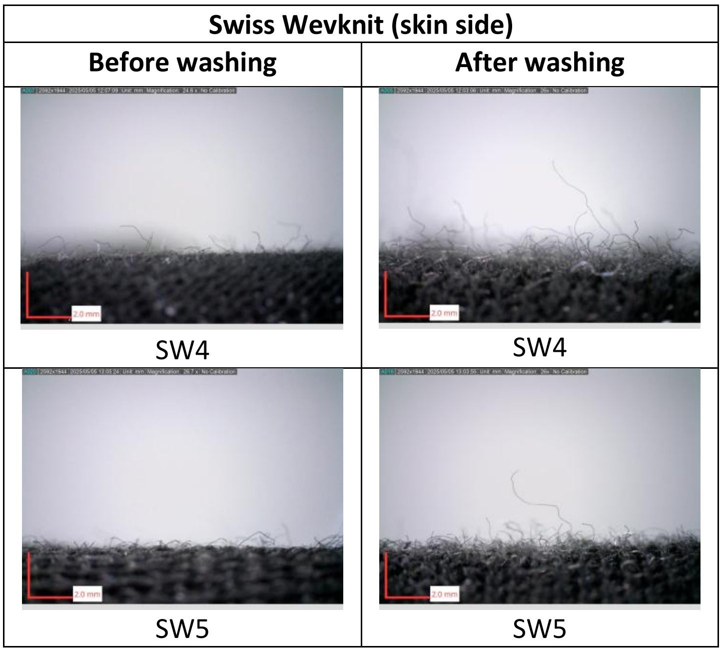


Figure 12. Fabric surface of Swiss wevknit before and after washing

Figure 13. Fabric surface of single jersey samples before and after washing

5.2 Test results of fabric samples without heat setting

This section presents individual test results from all fabric samples that have not been heat set, including the reference sample (heat setted). A table of summary is provided in table 14 (page 44) for comparison.

5.2.1 Horizontal wicking

5.2.1.1 Wetting time – liquid application on the skin side

Figure 14 presents the wetting time measurements with accordance to standard Wickview measurements of liquid application on the skin side. Table 14 and appendix 5 summarises the results where the liquid was applied on the skin and face side.

The time taken for moisture to appear on the face side differed considerably among the samples (figure 14). Most samples, including SW1, SW2, SW3, SW6, SJ8 and SJ9, showed rapid moisture detection with mean wetting times under 3 s. These results indicate efficient moisture transfer and consistent performance, as reflected by the standard deviation. In contrast, SW4 and SW5 exhibited significantly longer wetting times, averaging around 48 and 64 s respectively. These prolonged times suggest slower moisture movement through the fabric. Additionally, both samples showed large standard deviation, indicating high variability between tests. The reference sample had a wetting time of 4 s, slightly placing it among the slower performing structures but still outperform SW4 and SW5. The coefficient of variation for each sample can be seen in appendix 5. The highest variation was observed in SW4 and SJ7, with CVs of approximately 68% and 75%, respectively. SW5 and SJ8 also showed high variability. SW1, SW6 and SJ9 with the lowest CVs, all below 20%, suggesting high consistency and more reliable performance across repeated measurements. The reference sample showed a CV approximately 34%.

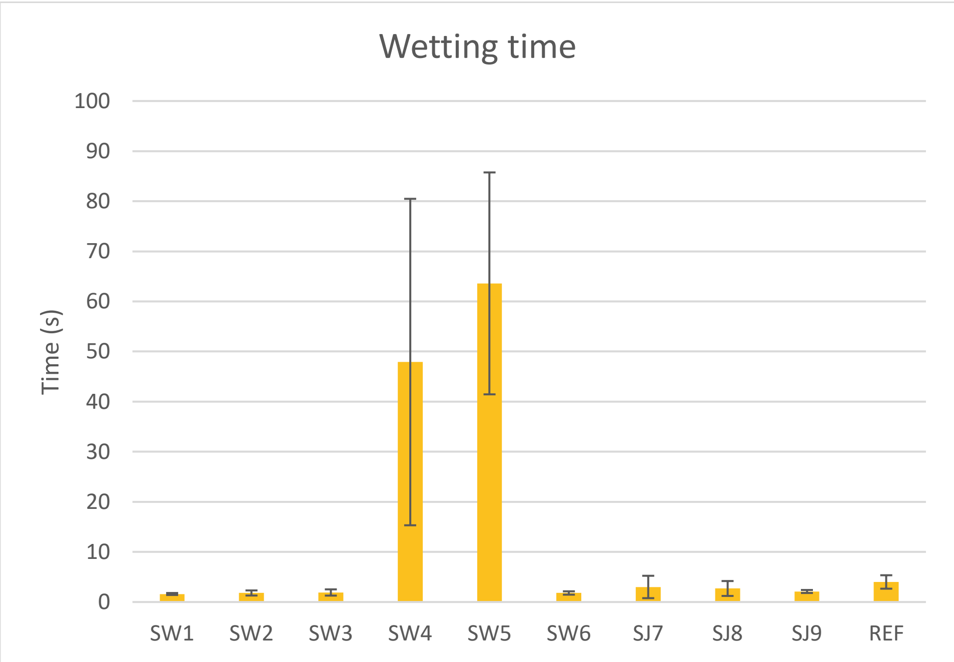


Figure 14. The time which moisture is detected on face side in seconds for all samples

Wetting time – liquid application on face side

Table 8 presents the wetting time for the modified Wickview test procedure for five samples. Among the samples, SJ9 exhibited the fastest wetting time, averaging 1.4 s, closely followed by SW1 and the reference sample, both with wetting times 1.5 seconds and 1.6 s respectively. SW4 and SW6 demonstrated the longest wetting times among them, averaging 2.2 s for both, with SW6 showing the highest variability as indicated by the larger standard deviations.

Table 8. Summary of all wetting times detected on the opposite side of liquid application for non-heat set samples, including test from standard and modified tests

Time (s)			
Sample ID	**Side**	**Mean & SD**	**CV (%)**
SW1	Skin	1.5 ± 0.22	15
SW4	Skin	2.2 ± 0.64	29
SW6	Skin	2.2 ± 1.47	67
SJ9	Skin	1.4 ± 0.23	17
REF	Skin	1.6 ± 0.3	19

5.2.1.2 Relative absorption rate – liquid application on skin side

Table 9 illustrates the percentage difference in the relative absorption rate between the face and skin side across ten samples, with liquid applied on the skin side (standard procedure). A higher value indicates a greater imbalance, meaning moisture retained predominantly on the skin side rather than transferring to the face side. SW5 exhibited an exceptionally high difference of approximately 190%, indicating that very little moisture was absorbed on the face side. This suggests poor one-way moisture transport, as the moisture did not effectively move away from the skin side to face side. Most other samples showed relatively low differences, SW1, SJ9 and REF had differences between 20-28%. SW2, SW3 and SJ8 and showed lower differences ranging from 10-14%. SW6 and SJ7 exhibited the lowest from 5% or below. During testing trials, sample SW4 showed hydrophobic behaviours, whereas the droplet did not absorb into the fabric but rather stayed on the surface (figure 15). Therefore, the test results from SW4 demonstrates as low as 0.1 %, which is a not a reliable value. Notably, SW5 and SW4 which have almost equal material distribution showed 190% and 0.1% relative absorption rate along with extremely high standard deviations, indicate that these measurements varied greatly among both tested specimens. Raw test data of SW4 can be found in Appendix 6.

Table 9. The difference (%) between face and skin side at 120s, including standard deviations

Relative absorption rate (%) applied on skin side			
Sample ID	**Side**	**Mean & SD**	**Diff (%)**
SW1	Face	3723 ± 910	28
	Skin	3723 ± 1259	
SW2	Face	4553 ± 1056	12
	Skin	5133 ± 599	
SW3	Face	4965 ± 927	10
	Skin	5484 ± 639	
SW4	Face	372 ± 518	0.1
	Skin	372 ± 517	
SW5	Face	11 ± 13	190
	Skin	436 ± 586	
SW6	Face	5190 ± 1360	2
	Skin	5067 ± 906	
SJ7	Face	2980 ± 4240	5
	Skin	3121 ± 1894	
SJ8	Face	99 ± 18	14
	Skin	87 ± 6	
SJ9	Face	4581 ± 1717	21
	Skin	5652 ± 383	
REF	Face	8111 ± 595	28
	Skin	6122 ± 443	

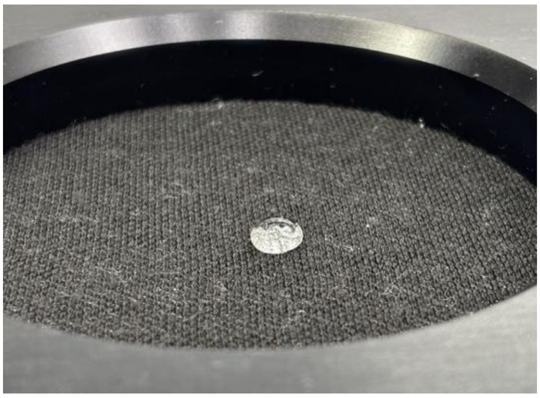


Figure 15. Visually observed water droplet still intact on SW4 after standard horizontal wicking test-

Relative absorption rate – Liquid application on the face side
The relative absorption rate with liquid application on the face side (modified) can be seen on table 10.

Sample SW1 showed the highest difference in absorption rate at 54%, followed by SW4 with 42% and SW6 with 25% difference. In contrast, SJ9 and the reference fabric showed minimal differences with 3% and 5% respectively during this configuration, indicating that both sides were almost equally wetted.

Table 10. Summary of average values of relative absorption rate in modified Wickview testing

Relative absorption rate (%) applied on face side (modified)			
Sample ID	**Side**	**Mean & SD**	**Diff (%)**
SW1	Skin	6016 ± 1483	54
	Face	3466 ± 1084	
SW4	Skin	1731 ± 246	42
	Face	2648 ± 860	
SW6	Skin	5713 ± 1792	25
	Face	4446 ± 897	
SJ9	Skin	4119 ± 1064	3
	Face	4254 ± 664	
REF	Skin	7421 ± 600	5
	Face	7028 ± 922	

5.2.1.3 Max wetted diameter – liquid application on skin side

The peak diameter of the wicked area can be seen on figure 16. Associated mean values, standard deviations and CVs can be found in appendix 5. These results come from the standard Wickview test, where the liquid was applied on the skin side. Most samples showed relatively high wicked diameter, >85 mm on both the face and skin sides. SW1-SW3 exhibited strong wicking behaviour on both sides of the fabric. Peak diameters ranged from 87 mm to nearly 100 mm, with minimal differences between face and skin sides. These samples showed small standard deviations, suggesting consistent performance and the CVs remained below 20%. SW4 and SW5 demonstrated the weakest spreading capacity. On the face side, SW4 reached only approximately 34 mm, and SW5 reached 21 mm. However, their skin sides performed better, reaching around 40 mm and 47 mm respectively. These samples had large standard deviations and CVs exceeding 90% on the face side and above 50 % on the skin side. The face side on SW6 had a max diameter of 97 mm with smaller standard deviations and a CV around 13%. The skin side reached nearly 95 mm in diameter and a CV around 6%. SJ7 had wicked diameters of 66 mm on the face side and 74 mm on the skin side. Both sides showed notable standard deviations, with CVs around 65% for the face side and 41% for the skin side. This shows inconsistency across measurements as a lack of reliability. The peak diameter of samples SJ8 and SJ9 delivered 99 mm and 95 mm (face side) and 87 mm and 101 mm (skin side), respectively. They had moderate standard deviations in comparison to the other samples and CVs ranging from 3-18%. The reference sample outperformed all others. It achieved the highest wicked diameters of 112 mm on the face side and 104 mm on the skin side and displayed the smallest standard deviations, supported by low CVs of 1-1.5%.

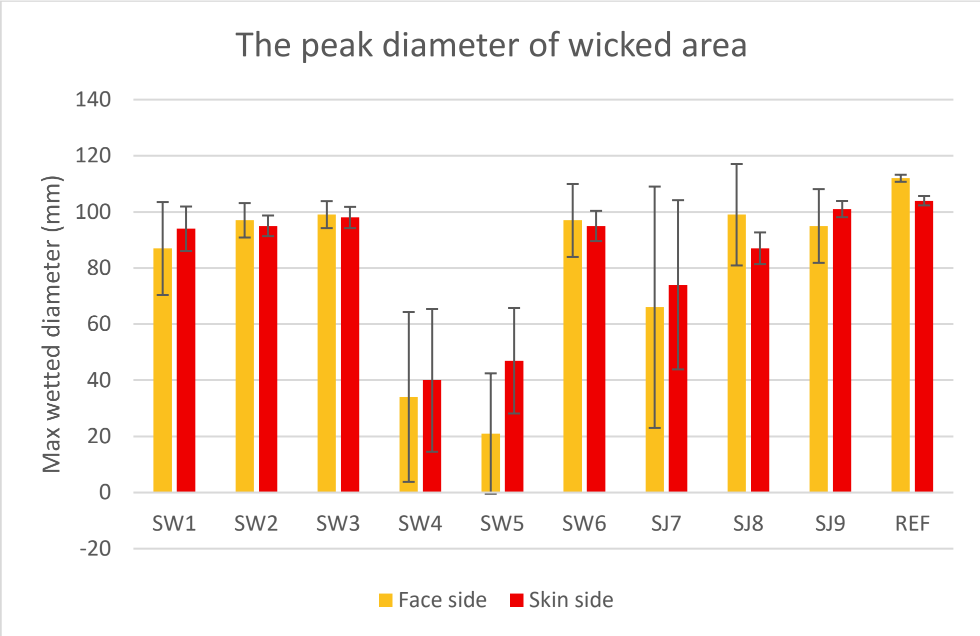


Figure 16. The peak diameter of the wicked area recorded at any time during the test in mm

5.2.1.4 Wicking area – liquid application on skin side

Wicking areas are shown in figure 17. Mean values, standard deviations and Cvs can be seen in appendix 5. Among the wevknit samples, SW1, SW2 and SW3, showed in the face side area with 3723 mm^2, 4553 mm^2, 4965 mm^2 respectively, while the corresponding skin side values were higher, 4937 mm^2, 5133 mm^2, 5484 mm^2. In contrast, SW4 and SW5 showed minimal wetted area, with both sides of SW4 registering 372 mm^2, and SW2 showing 11 mm^2 on the face side and 436 mm^2 on the skin side. These values indicate extremely limited spread. SW6 showed relatively balanced values between the two sides with 5190 mm^2 on the face side and 5067 mm^2 on the skin side, implying uniform wicking behaviour across the fabric. Among the single jersey samples, SJ7 had lower wicking values of 2980 mm^2 on the face side and 3121 mm^2 on skin side, accompanied by large standard deviations, suggesting high variability in performance. SJ8 demonstrated better face side wicking with 4934 mm^2 but slightly lower skin side performance of 3856 mm^2. Sample SJ9, however, had higher skin side wicking with 5652 mm^2 than face side with 4581 mm^2. Finally, the reference sample outperformed all others, with 8111 mm^2 on the face side and 6122 mm^2 on the skin side.

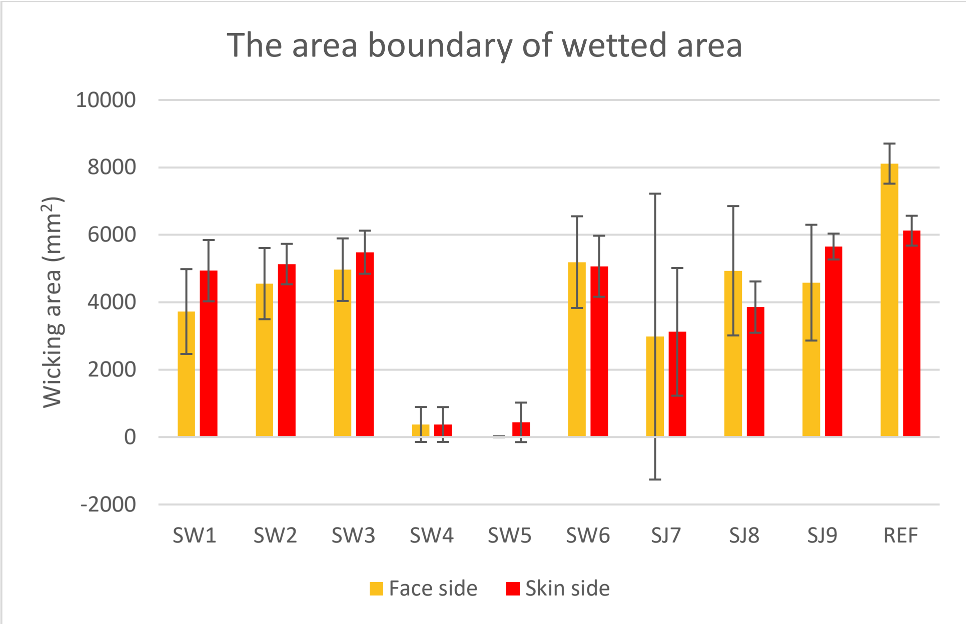


Figure 17. The area boundary of wetted area at 120 seconds in mm^2

5.2.2 VERTICAL WICKING

Vertical wicking test was conducted as a complementary to the horizontal wicking tests. This test was applied mainly to test sweat solutions with varying pHs.

The short-period wicking rates for all samples are shown in figure 18. The results varied significantly among the different fabric samples. The SW1, SW2 and SW3 samples demonstrated the highest wicking rates, especially with water, reaching up to 5.56 mm/s (SW1 and SW3), followed by alkaline solutions (e.g. SW2 with 6.67 mm/s) and acidic solutions (SW1 with 3.06 mm/s). Among these, SW2 showed the greatest variability. Indicated a larger standard deviation, particularly in the alkaline solution. In contrast, samples SW4 to SJ9 and the REF fabric, exhibited very low short-period wicking rates, generally below 0.5 mm/s, regardless of the test liquid. The REF sample showed the lowest values, approaching 0.2 mm/s, indicating negligible short-term capillary action. Water tended to yield the highest wicking rates across most fabrics, followed by alkaline and then acidic solutions. However, for samples containing less than 75 wt% Tencel, the solutions seem to have little effect on liquid transporting.

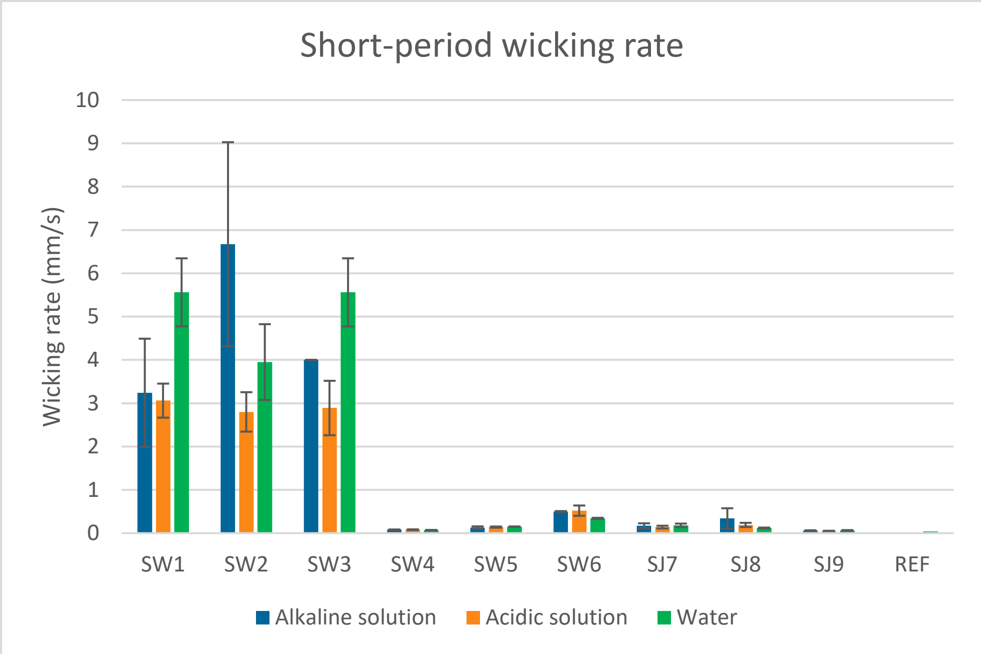


Figure 18. The short period wicking rate measured in mm/s of non-heat set samples

The long period wicking rates are presented in figure 19. Across all samples, the long-period wicking rates were considerably slower than the short-period rates, with a narrower range of values. The highest long-term wicking rates were observed for SW1, SW2 and SW3, reaching approximately 0.07 mm/s, with minimal variation between different test liquids. Other samples such as SW4-SW6 and SJ7-SJ9 demonstrated wicking rates between 0.02 and 0.04 mm/s, suggesting a limited but measurable ability to sustain moisture transport over time.

The REF fabric consistently showed the slowest long-period wicking rates, averaging 0.02 to 0.03 mm/s, with no major variation between test liquids. Unlike the short-period results, the differences between alkaline, acidic and water solutions were negligible in the long-period test, indicating that initial surface tension and capillary effects were more critical during the short-term period. In this case, liquids with varying pH had the same wicking behaviour for all samples.

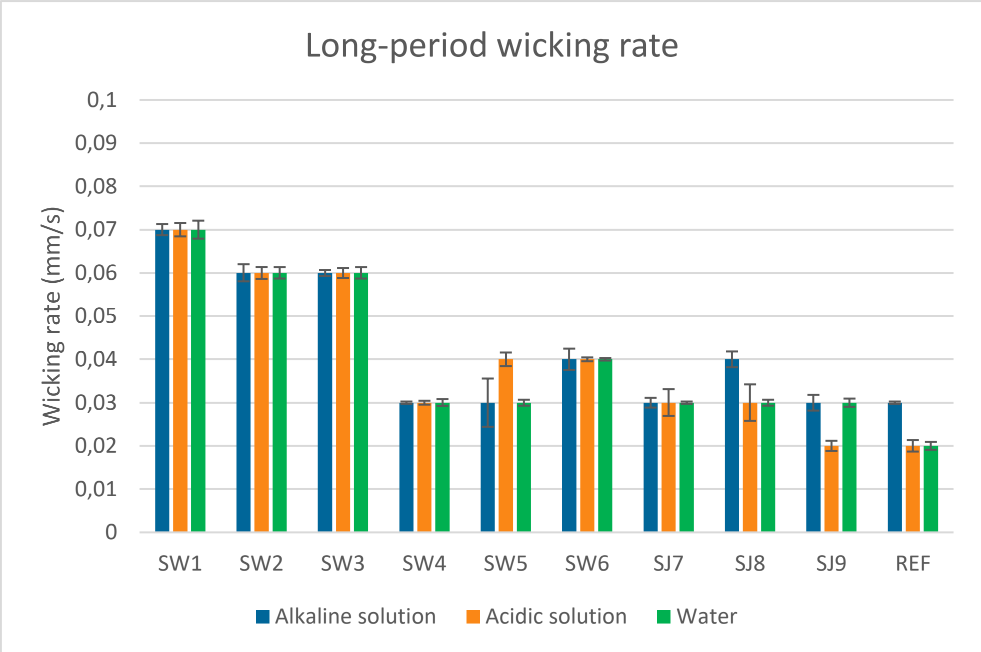


Figure 19. The long-period wicking rate measured in mm/s of non-heat seat samples

5.2.2.1 Surface tension

Figure 20 illustrates the results from surface tension measurements. Test results in surface tension for water, alkaline- and acidic solution was measured in mN/m. Alkaline solution exhibits the highest mean surface tension of 75.1 mN/m. Acidic solution and water have slightly lower values, approximately 75.6 mN/m and 74.8 mN/m, respectively and the difference between them is minimal. All three test liquids show minimal standard deviations.

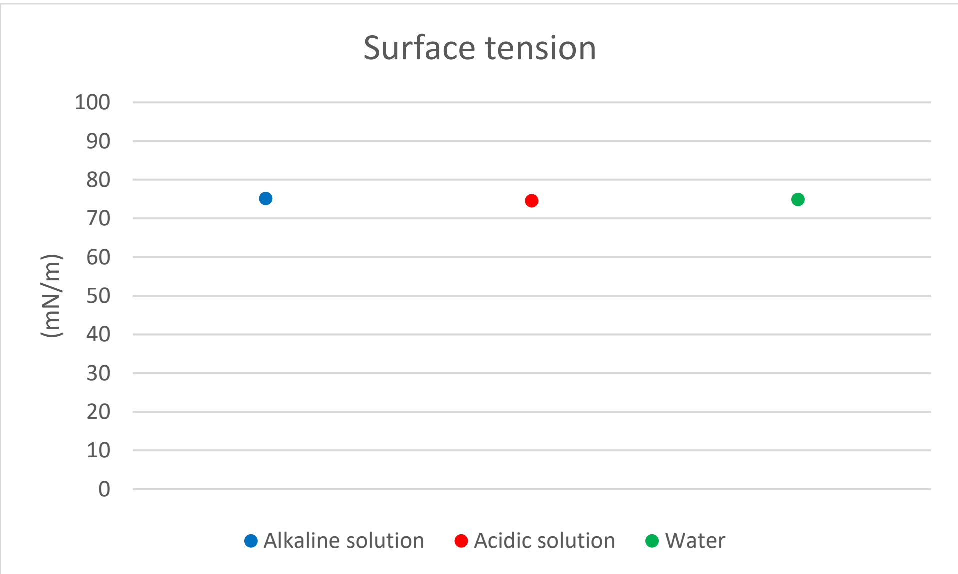


Figure 20. The surface tension of water, alkaline solution and acidic solution measured in mN/m

5.2.3 *Air permeability*

The results of the air permeability test showed some variability, as shown in figure 21. Among the samples, SJ9 exhibited the highest airflow rate at 3113 mm/s, followed closely by SJ7 at 3003 mm/s. In contrast, the reference fabric (REF) demonstrated the lowest air permeability at 1833 mm/s. Within the Swiss wevknit group, SW1, SW2 and SW6 showed relatively similar airflow values, ranging between 2327 mm/s and 2410 mm/s. SW4 and SW5 presented lower air permeability, recording 1963 mm/s and 2050 mm/s, respectively. Comparing single jersey and swiss wevknit structures, the single jersey samples (SJ7 and SJ9) achieved markedly higher air permeability than swiss wevknit (SW) samples, suggesting that the structural differences significantly influence airflow. SW samples displayed more moderate values, with SW4 having the lowest airflow among them. Overall, fabrics with single jersey structure allowed higher air passage, indicating a looser or more open knit compared to the swiss wevknit variants. The standard deviations suggest good measurement repeatability, although slight variation was observed, particularly in SW2, SJ7 and SJ8.

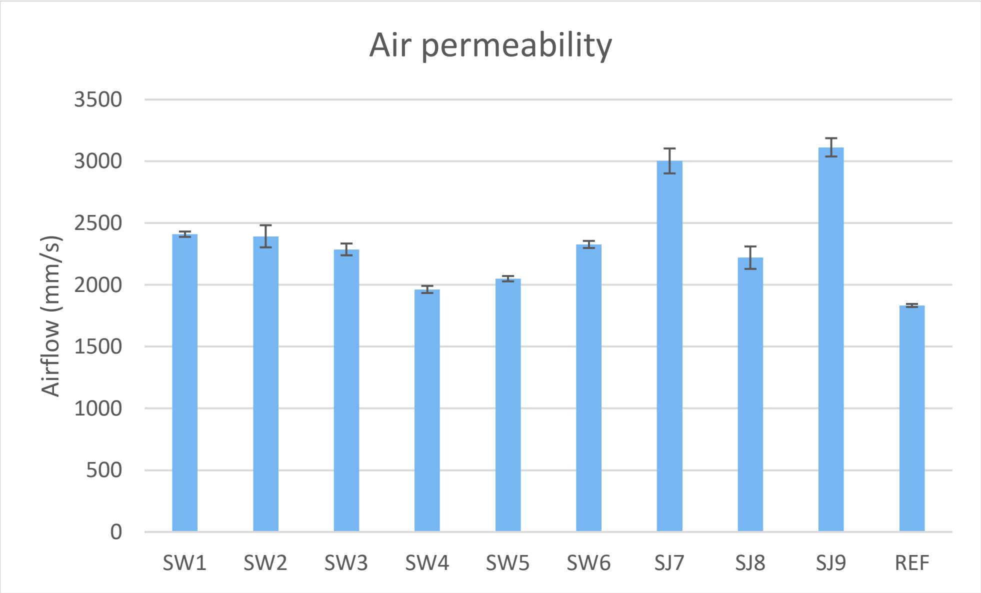


Figure 21. The airflow of fabric samples measured in mm/s

5.3 Test results of fabric samples with heat setting

Following section presents test results of those sample that have been heat set (SW1, SW4, SW6 and SJ9). For this section, “H” was added to the sample ID for better identification.

5.3.1 Horizontal Wickview

5.3.1.1 Wetting time – liquid application on skin side

The wetting times of samples that have been heat set can be seen in figure 22 and the average values can be found in appendix 7. Among the samples, SW1H, SW6H and SJ9H exhibited exceptionally fast wetting times, with an average of 1.5 seconds, 1.8 seconds and 1.7 seconds respectively, with minimal variation. In contrast, SW4H showed a delayed wetting time, averaging 37 seconds and showing substantial variability, as indicated by the large standard deviations.

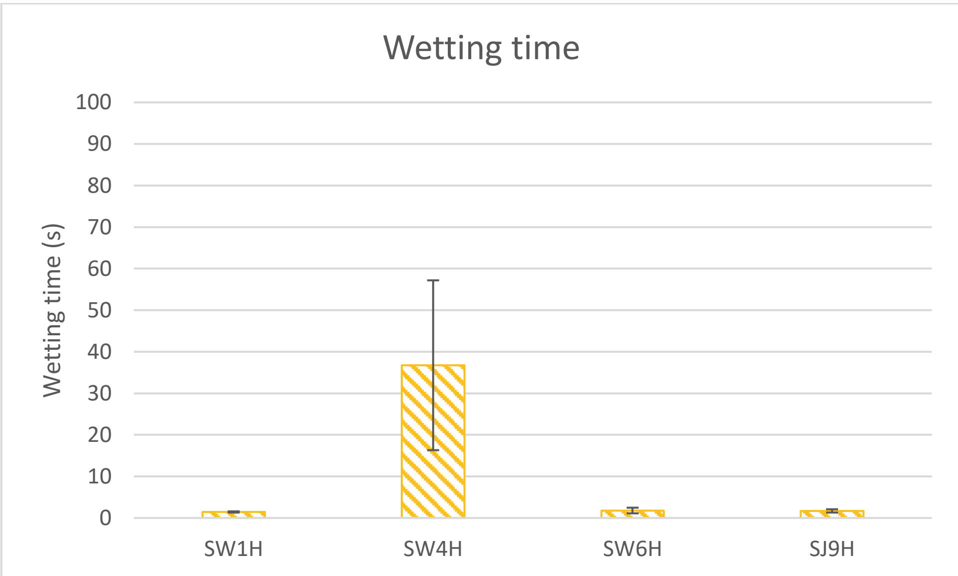


Figure 22. The time which moisture is detected on the face side in seconds

Wetting time – liquid application on the face side

The wetting time for the reversed liquid application of the four samples are presented in table 11. The sample SW1H and SJ9H demonstrated the fastest wetting time from the face side to the skin side. SW1H recorded a wetting time of 1.5 seconds, while SJ9H exhibited the fastest among the samples in 1.3 seconds. SW4H and SW6H average wetting times were 2.1 seconds and 2.5 seconds respectively. Both the samples had larger standard deviations, suggesting greater variability between the specimens.

Table 11. Summary of the time moisture is detected on the skin side, measured in modified configuration.

Wetting time (s)			
Sample ID	**Side**	**Mean & SD**	**CV (%)**
SW1H	Skin	1.5 ± 0.0006	0,04
SW4H	Skin	2.1 ± 0.889	42
SW6H	Skin	2.5 ±1.245	50
SJ9H	Skin	1.25 ± 0.335	27

5.3.1.2 Relative absorption rate – liquid application on skin side

In table 12 presents the difference in relative absorption rate between the face and skin sides, performed through the standard Wickview tests. Sample SW4H showed the highest difference, with an absorption rate difference of 72%. This suggests that the skin side absorbs significantly more moisture than the face side. SW1H, SW6H and SJ9H all exhibited lower differences with differences of 18%, 10% and 16% respectively.

Table 12. The % difference between skin & face side at 120s, including standard deviations

Relative absorption rate (%) applied on the skin side			
Sample ID	**Side**	**Mean & SD**	**Diff (%)**
SW1H	Face	3440 ± 1001	18
	Skin	4140 ± 1246	
SW4H	Face	240 ± 539	72
	Skin	113 ± 101	
SW6H	Face	4423 ± 1112	10
	Skin	4866 ± 1100	
SJ9H	Face	6353 ± 2197	16
	Skin	5387 ± 609	

Absorption rate – Liquid application on the face side

As shown in table 13 the samples exhibited varying levels of wetting in their absorption characteristics. SW4H demonstrated the highest difference in absorption rate between sides at 88%, indicating a pronounced one-sided absorption behaviour. SW1H and SW6H had differences of 49% and 36% respectively. Sample SJ9H exhibited the smallest difference at only 10%, indicating nearly equal moisture absorption on both sides.

Table 13. Summary of the % difference between face and skin side in modified setup

Relative Absorption rate (%) applied on the face side (modified)			
Sample ID	**Side**	**Mean & SD**	**Diff (%)**
SW1H	Skin	5407 ± 1246	49
	Face	3274 ± 682	
SW4H	Skin	1656 ± 236	118
	Face	4252 ± 865	
SW6H	Skin	5631 ± 2080	36
	Face	3898 ± 1548	
SJ9H	Skin	6253 ± 1613	10
	Face	5642 ± 894	

5.3.1.3 Max wetted diameter – liquid application on skin side

In figure 23 presents the maximum wetted diameter with liquid application on the skin side. Sample SW4H had the smallest peak diameter reaching 19.3 mm in the face side and 24.5 mm on the skin side with large error bars. SJ9H showed the largest diameter among the samples with 107mm on face side and 102 mm on skin side. SW6H followed closely with both sides almost the same diameter, reaching 94.7 mm on face side and 93.7 mm on skin side. SW1H had a slightly lower peak diameter of 86.9 mm on the face side and 86.6 mm on skin side.

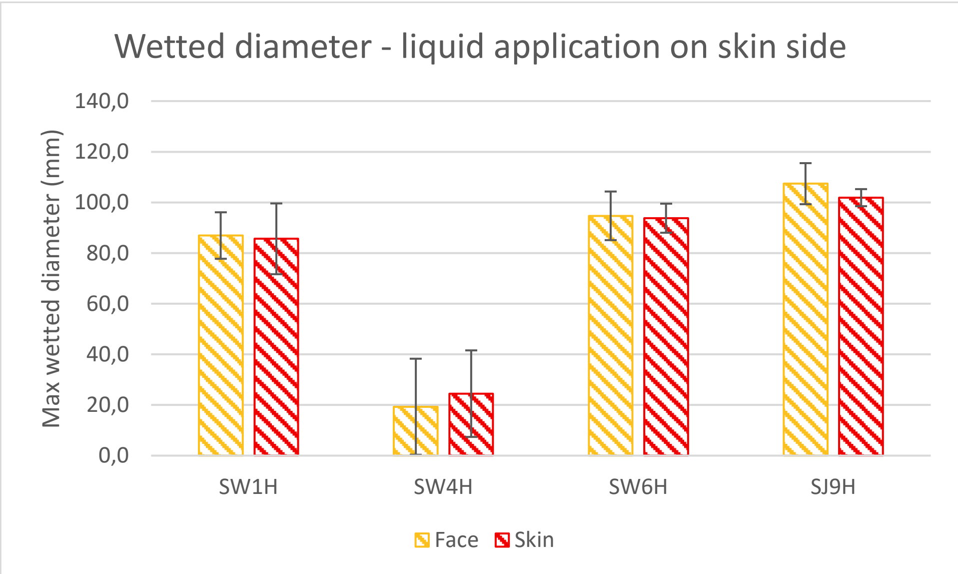


Figure 23. The peak diameter of the wicked area measured with liquid applied on the skin side, recorded at any time during the test in mm

5.3.1.4 Wicking area – liquid application on skin side

The wicking area measured in mm^2 can be found in figure 24. SJ9H showed the largest wicking area overall with 6353 mm^2 on the face side and 5387 mm^2 on the skin side. Sample SW6H measured with wicking area of 4423 mm^2 on the face side and slightly smaller area on the skin side with 4866mm^2. SW1H demonstrated 3440 mm^2 on the face side and 4140 mm^2 on the skin side, lower than SJ9H and SW6H overall. The lowest wicking capacity was observed in sample SW4H with values of 240 mm^2 on the face side and 113 mm^2on the skin side.

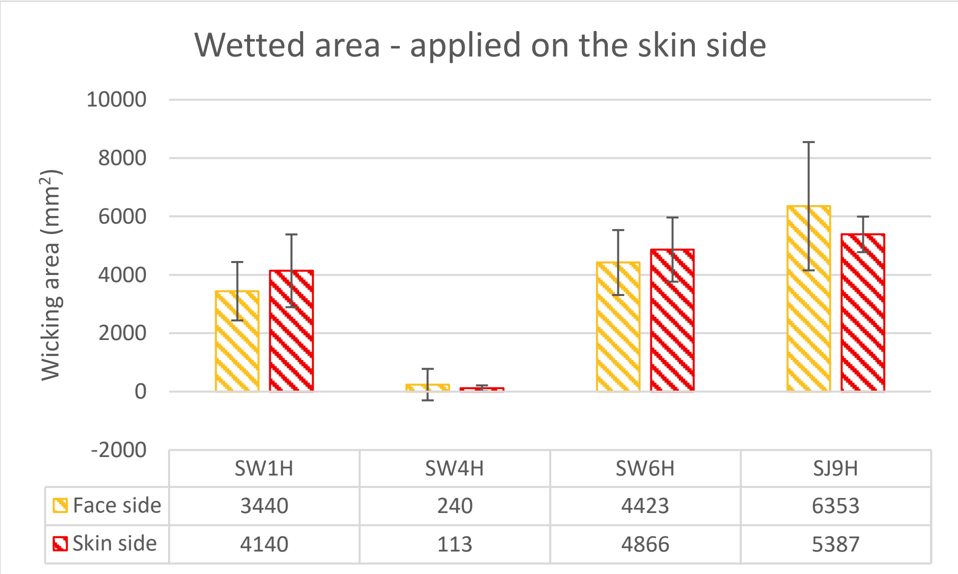


Figure 24. The area boundary of wetted area at 120 seconds in mm^2

5.3.1.5 Summary of horizontal wicking test

Down below provides an overview of all results from horizontal wicking, including standard and modified horizontal wicking tests and non-heat set vs heat set results. Table 14 presents result from standard horizontal wicking and table 14 presents modified horizontal wicking.

Standard test configuration

In the standard test configuration with accordance to AATCC 195, fibre composition of the samples showed varied results (table 14). Wetting time (s) was faster for those samples with 50 wt% of Tencel or higher. SW4 and SW5 with the least amount of Tencel had much longer wetting detected on the face side. The same pattern was observed in max wetted diameter (mm) in figure 16 and wicked area (mm^2) in figure 17. A higher relative absorption rate (%) indicate a higher difference between the face and skin side. The results show a difference ranging from 2% to 28% for samples with 50 wt% or higher Tencel. However, SW4 and SW5 had a difference of 0.1% to 190% despite having similar fibre compositions. The 190% difference could also be visually observed in figure 15 where the droplet was not absorbed by the fabric but instead sat atop, meaning no liquid was transferred to the other side. Given that both have similar fibre composition, these results suggest potential errors during testing. Mean values of skin and face sides in SW4 were identical (372), but individual specimen results (Appendix 6) showed variability. SW4 and SW5 continued to have higher standard deviations through all the measured parameters in horizontal wicking, showing inconsistencies in measurement.

Modified test configuration

Modified test of the horizontal wicking was applied to mimic the microclimate the inner gloves are worn where evaporation cannot escape the isolated environment inside the protective glove. This measures the fibres absorption ability without transferring the moisture to the skin side.

In the modified test configuration, parameters of wetting time (s) and relative absorption rate (%) was collected (table 15). In this setup, the liquid was applied on the face side containing Tencel. All the tested samples, including both non-heat set and heat setted samples had a relatively fast moisture detection on the skin side (opposite side of liquid application), with low standard deviations. The results do not show a simple linear relationship between Tencel content and wetting time. While both higher Tencel content in SW1 (75 wt%) and lower Tencel content in SJ9 (49 wt%) and REF (45 wt%) resulted in rapid wetting of <2 s, while sample SW6 with 50/50 wt% blend and SW4 with 25 wt% Tencel showed a slower response >2 s. This suggests that the fibre composition alone does not determine moisture transport, rather the interaction between fibre composition and fabric structure likely influences the formation of capillary channels. Also, SW6 did not have distinct hydrophobic or hydrophilic sides in comparison to the other samples. This sample was produced with both Tencel and polypropylene yarn present on both face and skin side. Which is likely why the results show a non-linear relationship between the Tencel wetting behaviour.

Table 14. Table of summary of results from standard horizontal wicking tests including mean and standard deviation.

Standard horizontal wicking						
	Sample ID	**Side**	**Wetting time (s)**	**Max wetted diameter (mm)**	**Wicked area (mm^2)**	**Relative absorption rate (%)**
Non-heat set	SW1	Face	1,6 ± 0.2	86.6 ± 16,5	3723 ± 910	28
		Skin	-	93.8 ±7.9	3723 ± 1259	
	SW2	Face	1,8 ± 0.5	97.3 ± 6.1	4553 ± 1056	12
		Skin	-	94.9 ± 3.7	5133 ± 599	
	SW3	Face	1,9 ± 0.6	99.3 ± 4.8	4965 ± 927	10
		Skin	-	97.6 ± 3.8	5484 ± 639	
	SW4	Face	47,9 ± 32.6	33.6 ± 30.2	372 ± 518	0,1
		Skin	-	40.3 ± 25.5	372 ± 517	
	SW5	Face	63,6 ± 22.2	20.6 ± 21.4	11 ± 13	190
		Skin	-	47.2 ± 18.8	436 ± 586	
	SW6	Face	1,8 ± 0.3	96.6 ± 13	5190 ± 1360	2
		Skin	-	94.7 ± 5.4	5067 ± 906	
	SJ7	Face	3 ± 2.2	66.3 ± 43	2980 ± 4240	5
		Skin	-	73.6 ± 30.1	3121 ± 1894	
	SJ8	Face	2,7 ± 1.5	99.3 ± 18.1	99 ± 18	14
		Skin	-	86.5 ± 5.7	87 ± 6	
	SJ9	Face	2,1 ± 0.3	95.2 ± 13.1	4581 ± 1717	21
		Skin		101.3 ± 2.9	5652 ± 383	
Heat set	**Sample ID**	**Side**	**Wetting time (s)**	**Max wetted diameter (mm)**	**Wicked area (mm^2)**	**Relative absorption rate (%)**
	SW1H	Face	1.5 ± 0.15	86.9 ± 9.2	3440 ± 1001	18
		Skin	-	85.6 ± 14	4140 ± 1246	
	SW4H	Face	36.8 ± 20.43	19.3 ± 19	240 ± 539	72
		Skin	-	24.5 ± 17.1	113 ± 101	
	SW6H	Face	1.8 ± 0.68	94.7 ± 9.6	4423 ± 1112	10
		Skin	-	93.7 ± 5.7	4866 ± 1100	
	SJ9H	Face	1.7 ± 0.4	107.4 ± 8.1	6353 ± 2197	16
		Skin	-	101.9 ± 3.4	5387 ± 609	
	REF	Face	4 ± 1.3	111.6 ± 1.3	111.6 ± 1.3	28
		Skin	-	103.8 ± 1.7	103.8 ± 1.7	

Table 15. Table of summary of results from modified horizontal wicking tests including mean and standard deviation.

Modified horizontal wicking				
	Sample ID	**Side**	**Wetting time (s)**	**Relative absorption rate (%)**
Non-heat set	SW1	Skin	1.5 ± 0.22	54
		Face	-	
	SW4	Skin	2.2 ± 0.64	42
		Face	-	
	SW6	Skin	2.2 ± 1.47	25
		Face	-	
	SJ9	Skin	1.4 ± 0.23	3
		Face	-	
Heat set	**Sample ID**	**Side**	**Wetting time (s)**	**Relative absorption rate (%)**
	SW1H	Skin	1.5 ± 0.0006	49
		Face	-	
	SW4H	Skin	2.1 ± 0.889	118
		Face	-	
	SW6H	Skin	2.5 ±1.245	36
		Face	-	
	SJ9H	Skin	1.25 ± 0.335	10
		Face	-	
	REF	Skin	1.6 ± 0.3	5
		Face	-	

5.3.2 Vertical wicking

For the heat setted samples, only deionised water was applied for vertical wicking test. This section also includes test results from non-heat setted samples to facilitate the comparison of the finishing treatment.

In the short-period wicking rate which can be seen in figure 25. Sample SW1H had an exceptionally high wicking rate of 4.67 mm/s with a larger standard deviation in comparison to other samples. SW4H had a very low average wicking rate of 0.063 mm/s. The average for SW6H reached 0.36 mm/s, higher than SW4H and SJ9H but still considerably slower than SW1H. Sample SJ9H performed the weakest but similar to SW4H, with a short-period wicking rate of 0.056 mm/s.

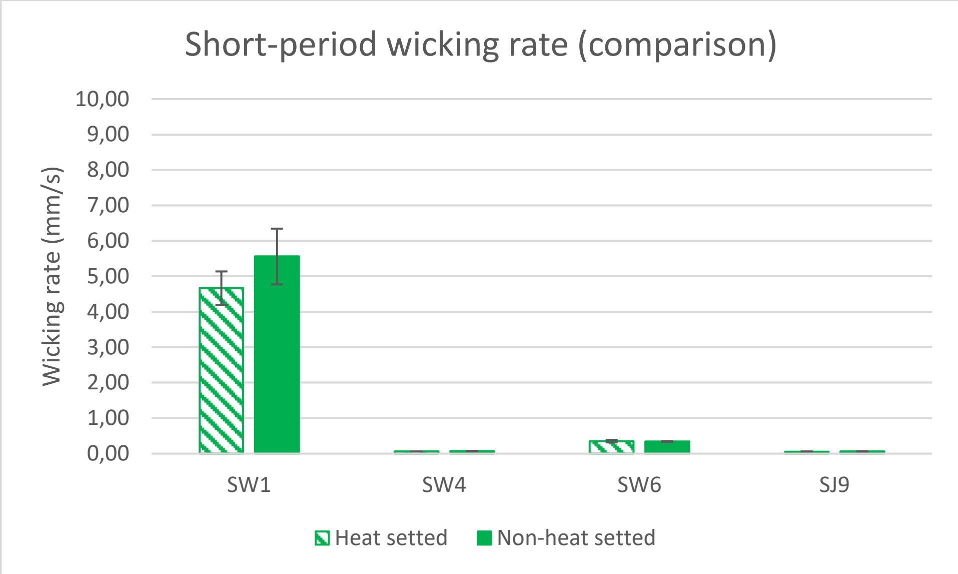


Figure 25. The short-period wicking rate in mm/s including non-heat set and heat set samples

A two-way ANOVA was conducted to statistically determine finishing treatment, or knitted structure could have an influence on the wicking rates (table 16). In the short-period, the statistical analysis shows that heat setting had no significant effect, with F-value being low as 1.8 and P-value averaging 0.19. While the knitted structure had a very strong, statistically significant effect, showing high F-value of 234 and P-value lower than 0.05. Calculation of ANOVA can be found in Appendix 8.

Table 16. Two-way ANOVA of non-heat setted and heat setted samples on the short-period wicking rates

Source of variation	F-value	P-value
Heat setting	1.882825	0.188946
Fabric structure	234.0326	2.01×10^{-13}

In figure 26 illustrate the long-period wicking rate. Sample SW1H again ranked the highest with a wicking rate 0.061 mm/s. This was followed by SW6H with an average wicking rate of 0.049 mm/s. SW4H showed a wicking rate of 0.028 mm/s. SJ9H demonstrated the slowest wicking rate of 0.024 mm/s. Overall, the wicking rate for the sample followed the same pattern in both short- and long-period wicking rate.

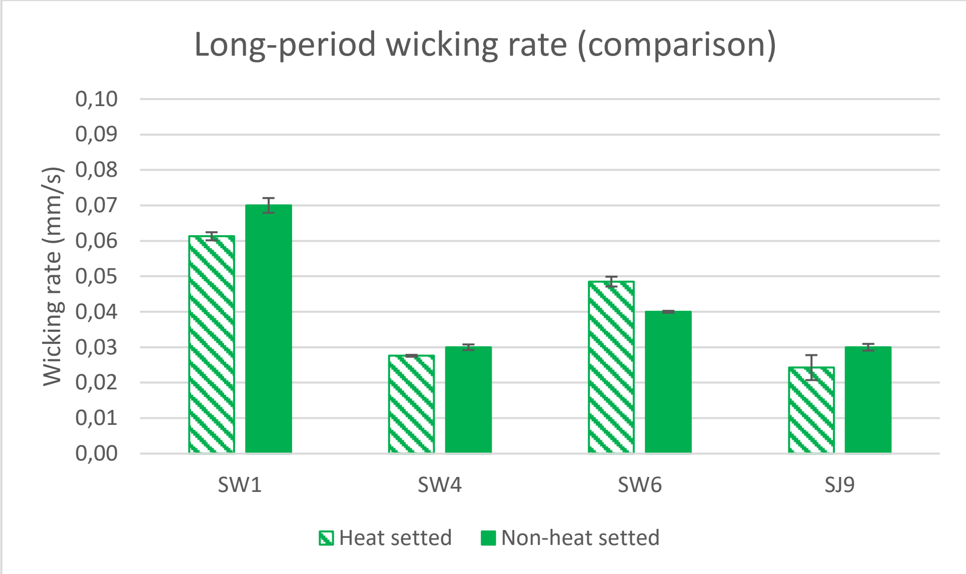


Figure 26. The long-period wicking rate measured in mm/s including non-heat set and heat set samples

A two-way ANOVA was conducted on the long-period wicking rates as well to determine whether the heat setting, or knitted structure had a significant influence on the vertical wicking rates (table 17). Analysis shows that heat setting had no effect at all, and knitted structure again showed a highly significant effect. Full ANOVA calculation can be found in Appendix 9.

Table 17. Two-way ANOVA of non-heat setted and heat setted samples on the long-period wicking rates

Source of variation	F-value	P-value
Heat setting	0	1
Fabric structure	489.8328	6.02×10^{-16}

In summary, material composition significantly effects both short- and long-period wicking. Heat setting does not.

5.3.3 Air permeability

Air permeability is illustrated for all fabrics in both non-heat set and heat set. The results are presented in figure 27. Sample SJ9 exhibited the highest air permeability in both states, with the heat set sample reaching 3023 mm/s (non-heat set with 3113 mm/s). SW4 had the lowest air permeability overall, dropping from 1963 mm/s to 1607 mm/s after heat setting. SW1 and SW6 with heat set airflow rate of 2207 mm/s and 2013 mm/s respectively (non-heat set with 2410 mm/s and 2327 mm/s respectively), both decreasing by approximately 200-300 mm/s post heat setting.

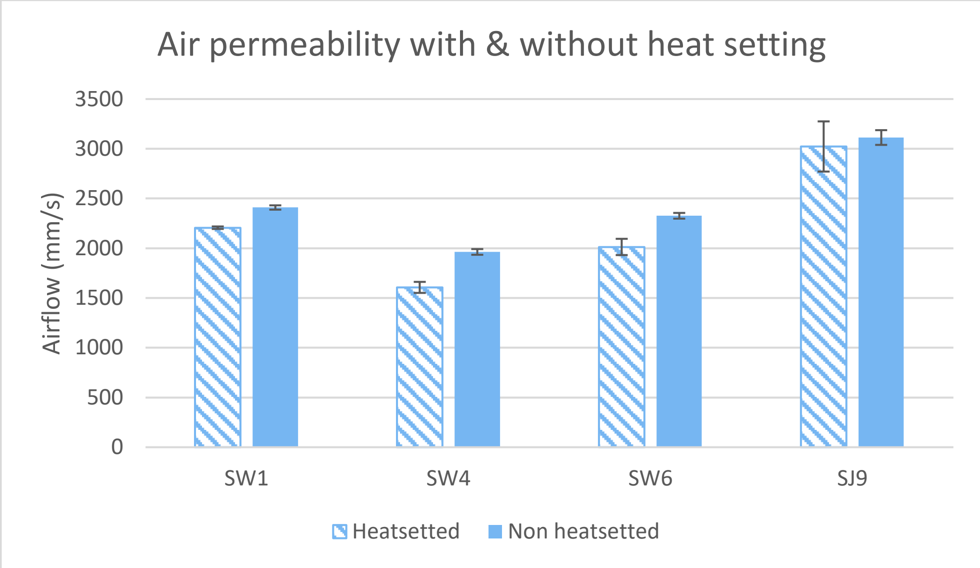


Figure 27. The airflow of heat set and non-heat set fabric samples measured in mm/s

To statistically analyse these results, a two-way ANOVA was performed. The F-value and P-value can be found in table 18. The analysis confirmed that heat setting had a significant impact on air permeability with an F-value of 22.87 and P-value of 0.0002. The textile structure (swiss wevknit and single jersey) itself also had a significant effect on air permeability, indicating the finishing treatment and structure are factors influencing and has a significant role in airflow. Full ANOVA can be found in Appendix 8.

Table 18. Two-way ANOVA on heat set vs. non-heat set on air permeability test

Source of variation	F-value	P-value
Heat setting	22.8699	0.0002
Fabric structure	114.111	5.17×10^{-11}

6. DISCUSSIONS

This section discusses the results in relation to the research questions: (1) what material distribution can be achieved using the same yarn type of Tencel and polypropylene, (2) to analyse the role of material composition in moisture transport, (3) to investigate the effect of knitted structures on wicking performance and (4) to compare moisture transport behaviour between water and sweat.

6.1 RESEARCH QUESTION 1

How is the percentage-wise composition of Tencel and polypropylene affected by a) different bindings and adjustments in b) machine parameters and c) yarn feeding positioning?

This section discusses the percentage-wise material composition based on the results from the knitting labs, focusing on different bindings, machine parameters and yarn feeding positioning affect the distribution of Tencel and polypropylene.

6.1.1 EFFECT OF BINDING TYPE

Two different bindings were used: Swiss wevknit (SW) and Single jersey (SJ). In the SW group, samples SW1-SW3 shared the same structure and yarn feeding positioning, resulting in a higher Tencel content (≈ 75 wt%), with minor differences of about 3% between them (see table 3). In contrast, samples SW4 and SW5 had opposite yarn feeding positioning, resulting in higher polypropylene content (≈ 75 wt%), though the difference between them was only 1.9%. SW6 was a blended variant, with no distinct hydrophobic or hydrophilic sides.

Within the SJ group, fabric sample SJ7 and SJ8 had the same structure and yarn feeding positioning, while SJ9 had the opposite yarn feeding. The composition differences within the SJ group were minimal, despite differing in yarn feeding positioning, showed only a 0.2% variation, all with higher polypropylene ratio.

This suggests that the type of binding influences how effectively yarn feeding can change material composition. In the SW binding, feeding adjustment led to meaningful shifts in composition, while in SJ, the same changes had little effect.

6.1.2 EFFECT OF MACHINE PARAMETERS

Adjustments to machine parameters such as yarn tension and stitch length did not significantly alter the percentage-wise material composition.

Yarn tension plays a significant role in the stitch formation process during circular knitting, influencing various aspects of fabric quality. The dynamics of needle movement during loop formation are affected by yarn tension, machine speed and fibre type. Increased yarn tension generally results in greater needle displacement, affecting stitch consistency and overall stitch quality (Duru, Candan & Mugan 2015). Moreover, research indicates that in knitted fabrics, yarn tension is often associated with and directly affects the stitch length, highlighting the importance of maintaining consistent yarn tension for achieving desired fabric properties (Dias & Lanarolle 2002). In weft knitted single jersey fabrics, yarn tension, alongside factors such as yarn count and stitch length, influences dimensional stability (Sarker et al. 2022). However, while these factors influence fabric properties, they do not impact material composition. Adjusting parameters such as yarn tension is therefore not a practical method for altering material ratios, and doing so may compromise the fabric quality or knitting stability.

Minor variations during knitting could also results from production inconsistencies. Each time a yarn was changed during fabric production, the machine required a few additional rounds to ensure that all needles were properly engaging with the new yarn. Also, the process of adjusting yarn tension during production also required a few rounds, since the machine required to be running while changing the yarn tension. These extra rounds, although necessary, could contribute to slight shifts in fibre distribution between fabric samples. Therefore, the observed percentage-wise differences within fabric groups may not be a result of intentional parameter changes, but rather a consequence of these unavoidable production steps. As such, the effect of machine parameter adjustments to change fibre composition remains minimal in practice.

6.1.3 Effect of yarn feeding positioning

The most notable changes in material composition were observed when yarn feeding positions were altered on the SW group. Reversing the placement of Tencel and polypropylene led to a clear shift in the dominant fibre content, switching from ≈ 75 wt% Tencel to ≈ 75 wt% polypropylene. Similar adjustments in the SJ group did not produce significant changes in material composition, where the result show higher polypropylene content in both cases. This indicates that yarn feeding positioning can influence material composition, but its effectiveness is dependent on the binding structure. In simpler bindings like single jersey, the impact is limited, whereas in structures like Swiss wevknit, more control over yarn placement is possible.

Overall, the ability to influence material composition within knitted fabrics is limited when only adjusting machine parameters or working within certain bindings. Among the three factors studied, yarn feeding positioning had the greatest impact, but only in the SW group. To better control material ratios, additional methods, such as using different yarn counts or more advanced plating technique may be required.

6.2 Research question 2

How does the fibre composition of polypropylene and Tencel affect moisture transport?

This section discusses how the fibre composition of polypropylene and Tencel influences moisture transport, based on the results from horizontal and vertical wicking tests. The findings highlight distinct differences in moisture management performance between the two fibres, which can be attributed to their inherent hydrophobic and hydrophilic nature, moisture regain and surface characteristics.

Horizontal wicking was selected as the primary method, as it allowed for controlled liquid application, quantitative image-based analysis and better representation of the isolated glove microclimate. However, this method was limited to testing with water. To address this limitation, vertical wicking was introduced as complementary method, enabling comparative testing with different sweat solutions. The combination of both methods provided a more comprehensive assessment of moisture transport.

6.2.1 Horizontal wicking

The samples containing more Tencel on the face side showed in general higher wetting, faster spreading and absorption both in the standard and modified horizontal wicking tests. The same behaviour was observed in the vertical wicking tests, both in short- and long-period wicking rates.

In the standard horizontal wicking with deionised water, the results showed faster wetting times and moisture spreading with samples containing more Tencel, both withing the SW and SJ group. While the samples containing more polypropylene (SW4 & SW5) showed the opposite effect, see table 14 for summary. This could possibly be due to Tencel's and polypropylenes fibre properties. This was more obvious within the SW samples containing ≈ 75 wt% of Tencel or higher. In the SJ group, which contained ≈ 45-49 wt% Tencel, demonstrated a slightly slower moisture transport behaviour. SW samples with the lowest Tencel content, ≈ 24-26 wt% Tencel underperformed. This behaviour is with accordance with literature.

Modified test of the horizontal wicking was applied to mimic the microclimate the inner gloves are worn where evaporation cannot escape the isolated environment inside the protective glove. This measures the fibres absorption ability without transferring the moisture to the skin side.

In the modified test configuration, where liquid was applied to ten face side, both wetting time and relative absorption rate were measured. All samples, regardless of heat setting, showed rapid moisture detection on skin side with low variation. No linear relationship was observed between Tencel content and wetting time, as both high (SW1, 75 wt%) and low (SJ9, 49 wt%; REF, 45 wt%) Tencel compositions resulted in fast wetting (<2 s), while SW6 (50/50 wt%) and SW4 (25 wt%) responded slowly (>2s). These results indicate that fibre composition alone does not determine moisture transport. Rather, the interaction between fibre type and fabric structure likely governs capillary action and liquid movement. The non-linear trend, particularly for SW6 may be due to its dual fibre surface composition, having Tencel and polypropylene on both sides, which could disrupt directional wicking compared to fabrics with distinct hydrophilic and hydrophobic surfaces.

However, this modified test has not seen executed in previous research. Therefore, the results from modified tests may lack sufficient evidence to confirm this certainty. The aim of including this modified version in this study was to evaluate whether the samples have the ability to keep the hands dry in a microclimate.

When relating these findings to inner glove applications, the variation in wetting time also reflects differences in liquid absorption. Shorter wetting times indicate that moisture passed through rapidly through the face side and appeared on the skin side, suggesting lower retention within the Tencel. Longer wetting times imply that the Tencel absorbed and held the moisture for a slightly longer period before breakthrough, meaning the skin side remained drier. From a comfort perspective, a slower wetting time may therefore be advantageous, as it could maintain a drier sensation on the side in contact with the skin.

In the application of inner gloves, sweat production on hands comes slower in comparison to the testing equipment. The testing equipment and environment is a speedier and faster setup to measure the moisture management. In a glove, sweat might come as a first phase as vapor and then transferring to liquid after a period of vapor buildup, that is when the capillary action helps transport the moisture from skin to face side.

The relative absorption rate results indicate differences in moisture transfer between face and skin side, but the direction of transfer is unknown, meaning that either the skin side or the face side remained drier or wetter. In this study, one can assume that the face side absorbed and retained more moisture due to Tencel fibre properties. Non-heat set samples (modified) shows decreasing differences from SW1 (54%) to sample SJ9 (3%), suggesting some fabrics maintain a more uniform moisture distribution while others had higher differences between sides. Heat setting generally increased the difference, particularly SW4 (118%), implying that thermal treatment can increase uneven moisture movement, likely by altering fibre alignment and capillary pathways. These findings together with wetting time show the fibre composition and heat setting (structure) influence how quickly moisture moves through the fabric and how evenly it is distributed between the two sides.

Additionally, not only does the inherent hydrophilicity and hydrophobicity in fibre influence the moisture transport. The fibre composition of polypropylene and Tencel shapes moisture transport through two contrasting mechanisms. Tencel provides an absorptions driven pathway and pulling water inside the fibre. Polypropylene, in contrast, offers a surface driven pathway, where the liquid movement relies entirely on loop geometry due to its lower surface energy as mentioned by Bechthold and Pham (2019). This creates not just a difference in hydrophilicity but a competition between absorption and spreading. Over time, this means Tencel tends to retain liquid and ability to lock moisture, whereas polypropylene promotes distribution and drying but cannot store moisture. In blended structures, these two complement each other with polypropylene directing moisture toward Tencel. Moisture transport is therefore not always about hydrophilic vs. hydrophobic and more about the balance determined by the fibre, structure and placement.

In summary, Tencel hydrophilic nature enhances both initial and sustained moisture transport, particularly when its content is sufficiently high. Polypropylenes hydrophobic restricts initial moisture uptake, resulting in slower wicking. However, an excessive amount of Tencel may lead to over absorption, making the fabric feel too damp during glove use. Therefore, while fibre compositions significantly influence moisture behaviour, optimal moisture transportation requires a balanced fibre blend and thoughtful fabric structure.

6.2.2 *Vertical wicking*

Similar trends can be observed in the vertical wicking tests, although test results of this test serve as secondary. Among the samples, those with higher polypropylene content (SW4 and SW5) exhibited slower vertical wicking in the short-period phase, reflecting polypropylenes hydrophobic characteristics. In contrast, samples with greater Tencel content, particularly SW1-SW3, demonstrated higher vertical wicking heights (figure 18).

On the other hand, in figure 18, single jersey samples, despite containing just under 50 wt% Tencel, showed the lowest vertical wicking heights among all samples. Within this group, SJ7 and SJ8, both with the same yarn position, showed faster short-period wicking compared to SJ9 and the reference fabric, which shared a reversed yarn position. This suggest that even within the same structure (binding), yarn positioning and stitch placement can influence initial moisture uptake. More regarding fabric structure will be discussed in research question 3.

Tencel's hydrophilic and fibrillar structure appears to support sustained capillary action over time. This aligns with Kadolph (2014), who highlight the high moisture retention of cellulosic fibres. Samples with high Tencel ratio (SW1-SW3) sustained moisture transport beyond the initial phase. Interestingly, the reference fabric, despite its comparable Tencel content, underperformed in both short- and long-period wicking rates, even compared to more polypropylene dominant samples like SW4 and SW5. This indicates that fabric structure and capillary pathways are critical factors, not just fibre type and content.

When observing the long-period wicking rates, results were consistent across fabric samples (figure 19). This pattern is supported by Lei et al. (2020), who found that in woven cotton fabrics, moisture transfer speed varied in the short-period phase and became steadier over time, regardless of structural differences. Similarly, Wang et al. (2022) confirmed that short-period rates are more sensitive to structural and environments conditions, whereas long-period rates reflect a more stable moisture transport behaviour.

In summary, the short-period wicking rate is important for understanding how fabrics handle sudden moisture exposure, while the long-period rate highlights their capacity for sustained moisture management. The findings demonstrate that fibre compositions play a critical role in moisture transport, with high ratio of Tencel fabrics showing great wicking performance compared to those with higher polypropylene content. Tencel's hydrophilic nature supports rapid and sustained capillary movement, while polypropylene hydrophobic nature limits moisture uptake, especially in short-term. However, fibre content alone is not decisive, seen in both horizontal and vertical wicking results. Fabric structure, yarn positioning and the spatial arrangement of fibres within the knit significantly influenced wicking rates. For instance, differences within the SJ group, despite similar fibre ratios, highlights the importance of fabric construction. Therefore, effective moisture management is the results of an interplay between fibre properties and fabric construction. The findings in this study, alongside prior research, highlight the importance of evaluating both properties to gain comprehensive understanding of fabric performance in practical moisture management scenarios.

6.3 Research question 3

How does fabric structure affect the moisture transportation properties?

Fabric structure plays an important role in determining the moisture transportation performance in textiles. Moisture management, particularly in applications where dryness is critical, such as inner gloves, relies not only in fibre type but also heavily on the way the fabric is constructed. The knitted structures influence capillary action, pore size distribution and pathways for liquid movement, all of which contribute to how effectively moisture is wicked away from the skin (Paul 2019).

6.3.1 Influence of bindings

The structure of a fabric plays an important role in determining its moisture transportation properties. This was evident throughout the study, particularly when comparing SJ and SW fabrics. SW fabrics, knitted on a double-bed at gauge E20, are denser and thicker, forming tighter loops and smaller pores. Conversely, SJ fabrics, produced on a single-bed machine with gauge E12, showed a looser, more open loop geometry. These differences in structure greatly influenced how moisture moved through the fabric.

Samples with higher polypropylene content (SW4 and SW5), a hydrophobic fibre, showed slower wicking performance. This was further influenced by their denser, more tightly knitted structures compared to single jersey fabrics. Such construction limited both short- and long-period wicking rates, highlighting that not only fibre content but also fabric structure plays a key role.

Even within the same knit type, the positioning of fibre had effects (mentioned earlier in research question 2). Samples SJ7 and SJ8 where Tencel was positioned on the front, showed faster wicking rates compared to SJ9 and the reference fabric, which had polypropylene at the front, despite having similar fibre content, see table 14. This highlights the importance of yarn arrangement and how structure influences the interaction between the fabric surface and moisture.

Vertical wicking tests further supported these findings. The reference fabric which featured a tighter construction with smaller and tighter loops (in comparison to the rest of SJ group), demonstrated a slower wicking rate overall. This suggests that more open or loosely packed structures may provide faster wicking, while denser construction may retain moisture or allowing longer pathways for liquid to travel. These observations are statistically supported by two-way ANOVA analysis; fabric structure significantly influenced both short- and long-period wicking rates, whereas heat setting had no significant effect (table 20 & 21)). These findings align with Rajagopalan, Aneja and Marchal (2001), who emphasized the importance of knit geometry in shaping moisture pathways.

During early horizontal wicking trials, some SJ samples including the reference sample, were so thin that the droplet passed through before absorption could be recorded. This suggests that fabrics which are too thin may not efficiently capture sudden sweat production, highlighting the need for adequate thickness alongside structural considerations (Sampath & Senthilkumar 2009; Rajagopalan, Aneja and Marchal 2001). A structure that is too tight may hinder vapor release, while on that is too loose may not support effective capillary action. A balanced knit, as noted by Sampath & Senthilkumar (2009), is important for optimal moisture transport.

6.3.2 *Heat set vs. non-heat set*

Heat setting was observed to impact the overall structure by tightening the stitches, leading to reduced porosity (fabric “airiness”) and lower air permeability. This was confirmed through the air permeability test conducted with two-way ANOVA, where heat set fabrics exhibited significantly lower airflow, with textile structures again showing strong statistical influence (table 22). While heat setting improved dimensional stability and appearance, it slightly decreased moisture transport efficiency due to the tighter construction. However, its impact on actual wicking performance, particularly in long-periods, was statistically insignificant. This aligns with findings by Sarkeshick et al. (2009), who noted that heat setting can tighten fabric structures and reduce porosity, especially in blends involving polypropylene.

While heat setting offers benefits, such as improved shrinkage control (during user phase), mechanical stability and improved aesthetics, these results suggests that it may negatively affect moisture transport performance (Sarkeshick et al. 2009). For applications such as inner gloves and other performance textiles where moisture management is essential, careful consideration must be given to the trade-off between dimensional stability and wicking efficiency.

6.3.3 *Fabric surface*

Surface characteristics, particularly hairiness, also played a role. Post-washing, some fabrics showed increased fibrillation, which affected absorbency (figure 12 & 13). Fabrics with hairy or rough surface had more contact points for moisture but could also exhibit higher surface energy and surface tension, causing the liquid to bead up rather than absorb (figure 15). This phenomenon was especially pronounced in samples like SW4, where the combination of surface hairiness and polypropylene content created a hydrophobic surface, where the droplets surface tension did not break. In such cases, moisture sat atop the fabric, consistent with the Cassie-Baxter model from 1944, where liquids rest on heterogenous surfaces and require external force to transition into absorption. Despite ten tests of each specimen of SW4, these samples consistently failed to proper transport moisture, pointing to the idea that surface texture significantly affects performance (Bhusan & Jung 2011). However, testing conditions lacked vibration or some kind of pressure while applying liquid to the fabric surface, that does not really simulate the real-life condition inside a glove where friction and pressure is applied to the fabric when wearing a tight glove.

Overall, fabric structure proved to be an important factor influencing moisture transport. Looser or more porous fabrics like SJ7-SJ9 facilitated better capillary action and quicker transport, while denser fabric like the reference fabric hindered it. Yarn arrangement and surface properties (hairiness) further influenced these effects. Heat setting, while valuable for stability and aesthetics, had limited influence on moisture movement. For applications such as inner gloves, where moisture management is crucial, careful consideration must be given to both macro and micro structural elements of the fabric structure.

6.4 Research question 4

How do moisture transport properties differ when tested with water vs. sweat?

The effect of liquid type on moisture transport was examined by comparing water, acidic sweat solution and alkaline sweat solution. Surface tension measurements (figure 20) showed minimal differences between the liquids.

These small variations suggests that all three liquids have very similar surface tension, and thus one would expect minor influence on capillary wicking. This expectation is supported by the long-period wicking rates data (figure 19), where all three liquids performed similarly across fabric types. The wicking rates differed at most 0.01 mm/s, indicating that fabric structure and fibre composition are the dominant factors influencing long-period moisture transport, rather than the fluid properties.

In the short-period wicking phase (figure 18), water sometimes showed higher rates, particularly in SW1 and SW3. However, this trend was not consistent across all samples. In many cases the difference between liquids were within the margin of variability, as shown by the standard deviations. This indicates that surface tension did not significantly affect initial moisture uptake under the tested conditions. Overall, while there are some fabric differences in short-period wicking rates between water and sweat solutions, the effect of liquid type appears to be minor, especially given the small surface tension differences. Therefore, for practical purposes, testing with water provides a comparable estimate of moisture transport performance as a testing media.

6.5 Inner gloves as a concept

By investigating how Tencel-polypropylene blends and knitted structures affect moisture transport, this research also discusses the potential to improve occupational comfort and hygiene while addressing broader sustainability challenges.

6.5.1 Environmental aspects

From an environmental perspective, polypropylene is lightweight and cost-effective but derived from fossil fuels, presenting challenges in biodegradability and end-of-life management (Kadolph 2014; Uddin 2022). Another environmental concern regarding the use of polypropylene is not only at end-of-life stage, but also during user stage, where it sheds microplastics into the environments (Priyadarshini et al. 2024; Thompson et al. 2024). Therefore, polypropylene, though is a very cost-effective and reliable with its desired fibre properties, it contributes to the currently environmental concerns. Establishing recycling methods, using recycled polypropylene or minimise the use of this fibre, could reduce environmental burden, while biobased alternatives may offer additional benefits.

Tencel, produced in a closed-loop system, is environmentally favourable, though higher costs may limit its adoption in cost-sensitive settings (Fletcher 2014). Production of Tencel is one of the most sustainable methods, but there is a concern regarding its end of use phase since it decomposes slowly in landfills and is not recyclable through conventional textile recycling systems according to Kadolph (2014). However, this statement is from 2014, and new research and development may have been adopted to this solution. Tencel may decompose slowly in landfills, but research have found that it breaks down significantly faster in marine conditions (Royer et al 2023). Tencel is also sensitive to acids and dilute alkalis and is vulnerable to damage from humid conditions (Kadolph 2014). These conditions apply to the microclimate of the inner gloves, where it is exposed to human sweat with certain pH and humid environment. These factors may affect the functionality on the long run, but also the lifespan of the gloves if Tencel breaks down after a time of use and must be replaced with a new pair due to damage and bacteria growth.

The production of the current inner gloves is first by producing the fabric, it is then cut and trimmed and later sewn to become a glove. All these processes require energy, generate solid waste and contribute to dust and noise pollution (Fletcher 2014). One way of reducing the energy consumption and production time is to implement whole garment or fully fashion knitting technology, where the products is finished with no further steps after knitting process. This eliminates many steps and saves energy, time and reduces waste generation.

Another environmental aspect is the end-of-life. The gloves are not mono material which makes the recycling complicated. It reduced the efficiency of sorting of the disposed gloves, recovery processes and probably results in downcycling or incineration (Anjimoon et al. 2024). Designing gloves for recyclability or disassembly at end-of-life can further support circular material flows, mitigating landfill overload and raw material extraction.

6.5.2 Social aspects

From a social perspective, glove comfort, moisture management and hygiene directly impact worker wellbeing. Discomfort or excess moisture can lead to skin irritation, reduced productivity and increased absenteeism (Symanzik et al 2022). This also affects individuals outside of their work since hand eczema impact the quality of life and contributes to psychological distress (Chiriac et al. 2020). Research have also found that conditions such as hand eczema can develop anxiety and depression on the long run (Long et al 2022), which results in some workers must call in sick. This reduces the work capacity, especially in healthcare where the it increases the strain on an already overburdened health systems (Symanzik et al. 2022). Adopting functional inner gloves for occupation groups where protective gloves are used daily is of high priority to protect these individuals. In different industrial sectors, women and men of varying ages need inner gloves to prevent hand related issues. To address this and to include all, inclusive design should account for variation in hand size, ensuring gloves are suitable for diverse populations. User-centred design principles can enhance comfort and hygiene, supporting occupational health and safety. Developing standards for comfort and hygiene may further mitigate social risks. To support inclusive design, further studies should consider variations in hand size, sensitivity and working conditions across different worker populations.

6.5.3 *ECONOMICAL ASPECTS*

Statistics from literature review show that hand eczema affects 10% of general population (arbetsmiljöverket 2012) and 21% hospital workers in Sweden (Hammerius et al. 2018). Hand eczema have substantial economical consequences and the condition can lead to absenteeism, job changes and reduced quality of life (Armstrong et al. 2022; Clemmensen et al. 2015). Skin conditions such as hand eczema in Denmark is already causing an economic burden (Clemmensen et al. 2015).

Economically, materials like Tencel tend to have higher upfront costs in comparison to polypropylene (Kadolph 2014). Yet, this must be weighed against potential long-term savings from extended glove lifespan, reduced replacement frequency, fewer skin related issues and decreased worker absenteeism. Strategies to balance cost and performance influence fibres blends, scaling production to reduce unit cost and policies that encourage investment in sustainable materials. By performing a cost-benefit analysis, one can get a holistic view to show long-term savings.

Taken together, sustainable glove design requires integrated thinking that balances environmental, social and economic factors. Performance must be aligned with material choices, lifecycle impact and worker wellbeing. Risk mitigation strategies, such as recycling, design and cost benefits should inform both product developer and policy makers. By adopting a systems perspective, future inner gloves can optimise comfort, reduce environmental impact and ensure economic feasibility, promoting material circularity and reduced discomfort in occupational settings. These strategies highlight glove design and must go beyond material selection, it requires integrated thinking that connects human needs, lifecycle impacts and economic feasibility.

7. Conclusions

This study examines how fibre compositions, fabric structure, and machine parameters influence the moisture transportation properties of knitted fabrics intended for inner gloves.

Among the three related knitting production factors, it was found that yarn feeding positioning had the most notable effect on the percentage-wise composition of Tencel and polypropylene, especially within Swiss wevknit binding. Adjusting machine parameters such as yarn tension and loop length and changing bindings alone resulted in only minor variations, indicating that it had a limited effect on material distribution when using these parameters.

The results also showed that fibre compositions play a significant role in moisture transportation performance. Fabrics with higher Tencel content exhibited faster and more sustained wicking both in vertical and horizontal directions, owing to Tencel's hydrophilic and absorbent nature. In contrast, higher polypropylene content fabrics demonstrated slower moisture uptake, reflecting the fibres inherent hydrophobicity and its lower surface energy. However, too much Tencel can result in excessive moisture retention, suggesting that careful balance of fibre types is necessary for optimal performance in glove applications. The study also found that fibre compositions alone does not determine moisture transportation behaviour in textiles.

Fabric structure also showed an important role influencing moisture transport. Looser knits like Single jersey facilitated capillary action, while denser knitted structures like Swiss wevknit resisted moisture transport. Material composition and surface texture further affected wicking behaviour. Although heat setting improved dimensional stability, it had little impact on long-period moisture uptake. Lastly, comparative testing with water and sweat solutions revealed only minor differences in surface tension, indicating that water is a valid and practical substitute for sweat in standard testing. Overall, these findings provide valuable guidance for the development of moisture transportation inner gloves, emphasising the importance of balancing fibre selection, fabric structure and manufacturing processes to achieve effective and reliable moisture management.

8. Future work

Altering machine parameters to change fibre compositions proved to be challenging and inefficient. Implementation of different yarn counts should be used in future work to manipulate the fibre compositions within a fabric.

Future studies should also consider of knitting using whole garment or fully fashion with no seams to produce full gloves to minimise the production steps. Further testing is required whether these whole gloves are functional and meet requirements.

Since the inner gloves exists within a microclimate where moisture cannot easily evaporate, it would be valuable to include rewet testing in future studies. This method could help evaluate how well the fabric retains moisture.

This study was limited to quantitative lab testing and did not assess actual glove wear. Therefore, user testing focused on comfort and real-world usability is recommended to gain fuller understanding of how the fabrics perform in practice.

As suggested by the findings, optimising the surface energy compatibility between the skin and fabric could be an interesting area to improve moisture transport efficiency.

Literature suggests that Tencel may be sensitive to humid environments and prone to bacterial growth. This raises concerns for users with sensitive skin or hygiene-related needs. Investigating bacterial development on the fabrics over time would be an important step, especially in setting where gloves are worn for long periods and not washed properly. Another area of interest regarding bacterial growth is to investigate if antimicrobial finishes can be applied to the fabric, without triggering any allergies for users.

Finally, in terms of sustainability, it would be worthwhile to explore whether recycled polypropylene can be used without compromising the fabrics moisture transport performance or overall quality.

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Appendix I. CIRCULAR KNITTING PROTOCOL 1 (SJ)

Yarn:	Tencel	Ne 30/1 A-100, White
	Polypropylene	Nm 1/50 Polycon, Schoeller, Black

Machine type:	Mayer & Cie, Relanit 0.8 6 feeding systems
Gauge:	12
Width:	55.9 cm
Feedings in use:	6 feeding system, 6/yarn type

No.	Machine parameters	Weight before	Weight after	Yarn type on feeders	Yarn tension	Loop length
7	**T:**570cm/round **PP:** 600cm/round	**T:** 516,64g **PP:** 1026,54g	**T:** 498,38 **PP:** 1007,03g	**T:** face **PP:** back	**T:** 3,4 **PP:** 0,9	19
8	**T:** 570cm/round **PP:** 570cm/round	**T:** 498,39g **PP:** 1007,03g	**T:** 480,48g **PP:** 988,05g	**T:** face **PP:** back	**T:** 3,4 **PP:** 3,4	19
9	**T:** 570cm/round **PP:** 570cm/round	**T:** 480,48g **PP:** 988,05g	**T:** 462,05g **PP:** 969,21g	**T:** back **PP:** face	**T:** 3,4 **PP:** 3,4	19

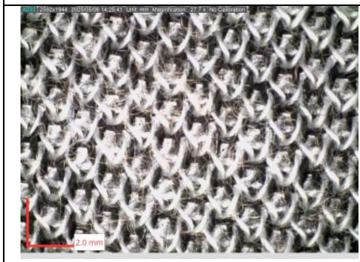
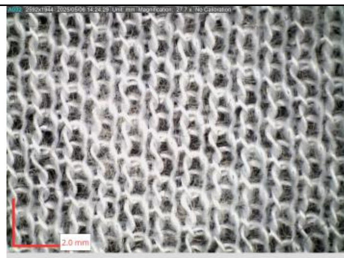
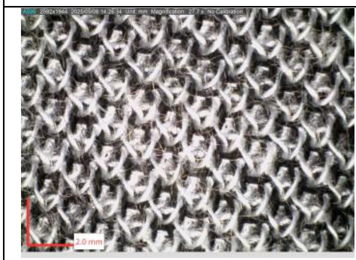
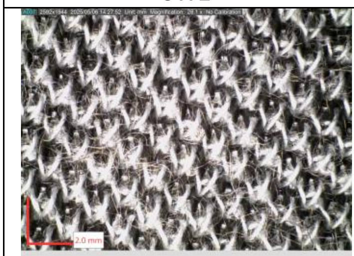
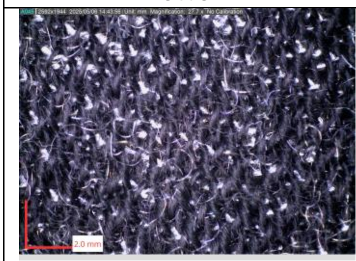
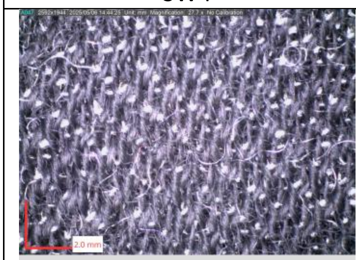
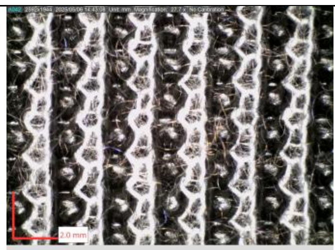
Appendix II. CIRCULAR KNITTING PROTOCOL 2 (SW)

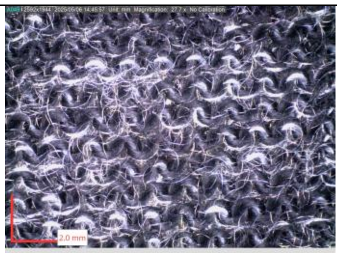
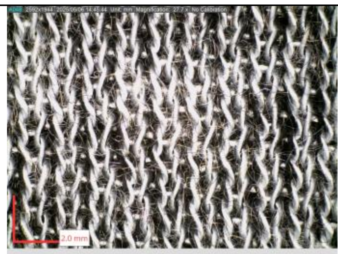
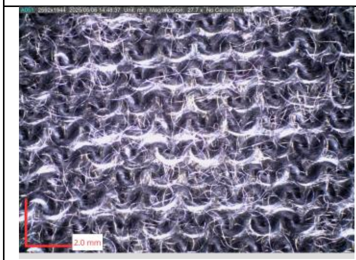
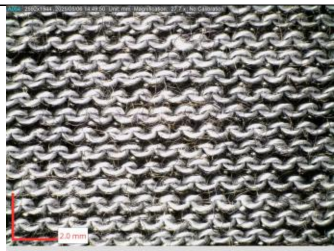
Yarn:	Tencel	Ne 30/1 A-100, White
	Polypropylene	Nm 1/50 Polycon, Schoeller, Black

Machine type: Mayer & Cie,
OVJA 1.6 EE
48 feeding systems
Gauge: 20
Width: 140 cm
Feedings in use: 16 feeding system, 8/yarn type

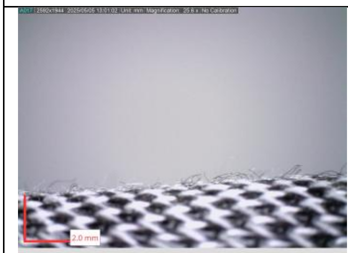
No.	Weight before	Weight after	Yarn type on feeders	Yarn tension	Loop length
1	**T:** 740,25g **PP**: 1204,91g	**T:** 677,83g **PP:** 1183,87g	**T:** 1, 3, 5, 7, 9, 11, 13, 15 **PP:** 2, 4, 6, 8, 10, 12,14, 16	4	**PP:** 10
2	**T:** 677,83g **PP:** 1183,87g	**T:** 615,25g **PP:** 1165,38g	**T:** 1, 3, 5, 7, 9, 11, 13, 15 **PP:** 2, 4, 6, 8, 10, 12,14, 16	2	**T:** 10 **PP:** 10
3	**T:** 615,25g **PP:** 1165,38g	**T:** 556,99g **PP:**1145,53g	**T:** 1, 3, 5, 7, 9, 11, 13, 15 **PP:** 2, 4, 6, 8, 10, 12,14, 16	2	**T:** 5 **PP:** 10
4	**T:** 556,99g **PP:** 1145,53 g	**T:** 534,82g **PP:** 1083,14g	**T:** 2, 4, 6, ,8 10, 12, 14, 16 **PP:** 1, 3, 5, ,7 ,9, 11, 13, 15	2	**T:** 10 **PP:** 10
5	**T:** 534,82g **PP:** 1083,14g	**T:** 516,64g **PP:** 1026,54g	**T:** 2, 4, 6, ,8 10, 12, 14, 16 **PP:** 1, 3, 5, 7, 9, 11, 13, 15	4	**T:** 10 **PP:** 10
6	**T:** 443,84 **PP:** 769,56	**T:** **PP:**	**T:** 1,2,5,6, 9, 10, 13, 14 **PP:** 3, 4, 7, 8, 11, 12, 15, 16	4	**T:** 10 **PP:** 10

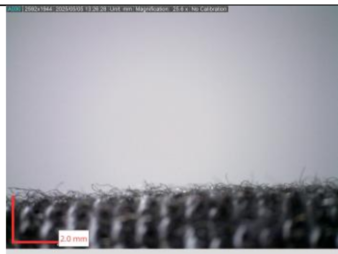
Appendix III. MICROSCOPIC IMAGES OF KNITTED STRUCTURE

Swiss wevknit	
Skin side	**Face side**
 SW1	 SW1
 SW2	 SW2
 SW3	 SW3
 SW4	 SW4
 SW5	 SW5
 SW6	 SW6

Single Jersey	
Skin side	**Face side**
 SJ7	 SJ7
 SJ8	 SJ8
 SJ9	 SJ9
 REF	 REF

Appendix IV. MICROSCOPIC IMAGES OF FABRIC SURFACE

Swiss Wevknit (skin side)	
Before washing	**After washing**
 SW1	 SW1
 SW2	 SW2
 SW3	 SW3
 SW4	 SW4
 SW5	 SW5
 SW6	 SW6

Single Jersey (skin side)	
Before washing	**After washing**
 SJ7	 SJ7
 SJ8	 SJ8
 SJ9	 SJ9
(Not available)	 REF

Appendix V. HORIZONTAL WICKING (NON-HEAT SETTED)

Table of summary of wetting time in standard and modified horizontal wicking for non-heat set samples.

Time (s)			
Sample ID	**Side**	**Mean & SD**	**CV (%)**
SW1	Face	1,6 ± 0.2	12
	Skin (modified)	1.5 ± 0.22	15
SW2	Face	1,8 ± 0.5	28
SW3	Face	1,9 ± 0.6	33
SW4	Face	47,9 ± 32.6	68
	Skin (modified)	2.2 ± 0.64	29
SW5	Face	63,6 ± 22.2	35
SW6	Face	1,8 ± 0.3	19
	Skin (modified)	2.2 ± 1.47	67
SJ7	Face	3 ± 2.2	75
SJ8	Face	2,7 ± 1.5	55
SJ9	Face	2,1 ± 0.3	14
	Skin (modified)	1.4 ± 0.23	17
REF	Face	4 ± 1.3	34
	Skin (modified)	1.6 ± 0.3	19

Table of summary of max wetted diameter in standard horizontal wicking for non-heat set samples

Max wetted diameter (mm) applied in the skin side			
Sample ID	**Side**	**Mean & SD**	**CV (%)**
SW1	Face	86.6 ± 16,5	19
	Skin	93.8 ±7.9	8
SW2	Face	97.3 ± 6.1	6
	Skin	94.9 ± 3.7	4
SW3	Face	99.3 ± 4.8	5
	Skin	97.6 ± 3.8	4
SW4	Face	33.6 ± 30.2	90
	Skin	40.3 ± 25.5	63
SW5	Face	20.6 ± 21.4	104
	Skin	47.2 ± 18.8	40
SW6	Face	96.6 ± 13	13
	Skin	94.7 ± 5.4	6
SJ7	Face	66.3 ± 43	65
	Skin	73.6 ± 30.1	41
SJ8	Face	99.3 ± 18.1	18
	Skin	86.5 ± 5.7	7
SJ9	Face	95.2 ± 13.1	14
	Skin	101.3 ± 2.9	3
REF	Face	111.6 ± 1.3	1
	Skin	103.8 ± 1.7	2

Table of summary of wicked area in standard horizontal wicking for non-heat set samples

Wicked area (mm^2)			
Sample ID	**Side**	**Mean & SD**	**CV (%)**
SW1	Face	3723 ± 910	34
	Skin	3723 ± 1259	18
SW2	Face	4553 ± 1056	23
	Skin	5133 ± 599	12
SW3	Face	4965 ± 927	19
	Skin	5484 ± 639	12
SW4	Face	372 ± 518	139
	Skin	372 ± 517	139
SW5	Face	11 ± 13	124
	Skin	436 ± 586	134
SW6	Face	5190 ± 1360	26
	Skin	5067 ± 906	18
SJ7	Face	2980 ± 4240	142
	Skin	3121 ± 1894	61
SJ8	Face	99 ± 18	39
	Skin	87 ± 6	20
SJ9	Face	4581 ± 1717	37
	Skin	5652 ± 383	7
REF	Face	8111 ± 595	7
	Skin	6122 ± 443	7

Appendix VI. Raw test data for sample SW4 (non-heat set) extracted from Wickview

WickView Results					
Results			Wetting time	Relative absorption rate	Max wetted diameter
Face	Reference	Sample Orientation	Area Actual First Seen At (Secs)	Area Boundary At Time 120,00 (mm²)	Max Length (XY) Max (mm)
	SW4_1	Horizontal	35,501	33,434	8,691
	SW4_2	Horizontal	8,002	862,008	71,144
	SW4_3	Horizontal	37	39,069	10,325
	SW4_4	Horizontal	27,001	1696,368	83,412
	SW4_5	Horizontal	115,501	0	0,945
	SW4_skin_10	Horizontal	60,501	11,372	6,822
	SW4_skin_6	Horizontal	92	0,563	1,714
	SW4_skin_7	Horizontal	9,001	344,076	39,373
	SW4_skin_8	Horizontal	39	541,558	66,484
	SW4_skin_9	Horizontal	55,001	196,383	46,772
		Mean	47,8508	372,4831	33,5682
		Std deviation	32,58434655	518,2951946	30,23454142
		CV (%)	68,09571952	139,1459625	90,06899809
Skin	Reference	Sample Orientation	Area Actual First Seen At (Secs)	Area Boundary At Time 120,00 (mm²)	Max Length (XY) Max (mm)
	SW4_1	Horizontal	4,502	190,598	41,576
	SW4_2	Horizontal	3,5	225,1	42,268
	SW4_3	Horizontal	4,5	1752,554	87,186
	SW4_4	Horizontal	3,501	874,627	67,775
	SW4_5	Horizontal	4,5	48,143	8,883
	SW4_skin_10	Horizontal	4,502	203,054	52,002
	SW4_skin_6	Horizontal	4	45,972	9,188
	SW4_skin_7	Horizontal	3,501	290,305	57,364
	SW4_skin_8	Horizontal	3,502	48,144	27,944
	SW4_skin_9	Horizontal	4,001	42,509	8,836
		Mean		372,1006	40,3022
		Std deviation		517,0000878	25,46454228
		CV (%)		138,9409444	63,18400059

Appendix VII. HORIZONTAL WICKING (HEAT SETTED)

Table of summary of wetting time in standard and modified horizontal wicking for heat setted samples

Wetting time (s)			
Sample ID	**Side**	**Mean & SD**	**CV (%)**
SW1H	Face	1.5 ± 0.15	10
	Skin (modified)	1.5 ± 0.0006	0,04
SW4H	Face	36.8 ± 20.43	56
	Skin (modified)	2.1 ± 0.889	42
SW6H	Face	1.8 ± 0.68	38
	Skin (modified)	2.5 ±1.245	50
SJ9H	Face	1.7 ± 0.4	24
	Skin (modified)	1.25 ± 0.335	27

Appendix VIII. ANOVA – Vertical wicking

Short-period wicking

Anova: Two-Factor With Replication

SUMMARY	SW1	SW4	SW6	SJ9	Total
Non heatsetting					
Count	3	3	3	3	12
Sum	16,667	0,217992	1,013165	0,186038	18,08419
Average	5,555667	0,072664	0,337722	0,062013	1,507016
Variance	0,926296	2,26E-05	0,000317	0,000175	6,14239
Heatsetting					
Count	3	3	3	3	12
Sum	14	0,189295	1,055914	0,169157	15,41437
Average	4,666667	0,063098	0,351971	0,056386	1,28453
Variance	0,333333	6,34E-07	0,001759	2,74E-05	4,236044
Total					
Count	6	6	6	6	
Sum	30,667	0,407287	2,069079	0,355195	
Average	5,111167	0,067881	0,344847	0,059199	
Variance	0,740948	3,67E-05	0,000891	9,05E-05	

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Heat setting	0,296999	1	0,296999	1,882825	0,188946	4,493998
Knitted structure	110,7499	3	36,91665	234,0326	2,01E-13	3,238872
Interaction	0,888971	3	0,296324	1,878541	0,173909	3,238872
Within	2,523863	16	0,157741			
Total	114,4598	23				

Long-period wicking

Anova: Two-Factor With Replication

SUMMARY	SW1	SW4	SW6	SJ9	Total
Non heatsetted					
Count	3	3	3	3	12
Sum	0,2	0,08	0,127222	0,077778	0,485
Average	0,066667	0,026667	0,042407	0,025926	0,040417
Variance	6,48E-06	9,26E-07	1,03E-07	1,34E-06	0,000299
Heatsetted					
Count	3	3	3	3	12
Sum	0,183889	0,082778	0,145556	0,072778	0,485
Average	0,061296	0,027593	0,048519	0,024259	0,040417
Variance	1,95E-06	1,03E-07	2,88E-06	1,86E-05	0,000257
Total					
Count	6	6	6	6	
Sum	0,383889	0,162778	0,272778	0,150556	
Average	0,063981	0,02713	0,045463	0,025093	
Variance	1,2E-05	6,69E-07	1,24E-05	8,82E-06	

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Heat setting	0	1	0	0	1	4,493998
Knitted structure	0,005953	3	0,001984	489,8328	6,02E-16	3,238872
Interaction	0,000105	3	3,49E-05	8,617989	0,001237	3,238872
Within	6,48E-05	16	4,05E-06			
Total	0,006122	23				

Appendix IX. ANOVA – Air permeability

Anova: Two-Factor With Replication

SUMMARY	SW1	SW4	SW6	SJ9	Total
Heat setted					
Count	3	3	3	3	12
Sum	6620	4820	6040	9070	26550
Average	2206,667	1606,667	2013,333	3023,333	2212,5
Variance	233,3333	4633,333	10033,33	95433,33	310293,2
Non heatsetted					
Count	3	3	3	3	12
Sum	7230	5890	6980	9340	29440
Average	2410	1963,333	2326,667	3113,333	2453,333
Variance	700	1233,333	1233,333	8233,333	191242,4
Total					
Count	6	6	6	6	
Sum	13850	10710	13020	18410	
Average	2308,333	1785	2170	3068,333	
Variance	12776,67	40510	33960	43896,67	

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Treatment	348004,2	1	348004,2	22,86993	0,000204	4,493998
Textile structure	5209179	3	1736393	114,1113	5,17E-11	3,238872
Interaction	64245,83	3	21415,28	1,407357	0,277117	3,238872
Within	243466,7	16	15216,67			
Total	5864896	23				