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# Thermal Resistance and Moisture Management Behaviour of Nettle/Polyester Nonwoven Fabrics
*Toplotni upor in prenos vlage skozi vlaknovine iz vlaken koprive in poliestra*

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## Abstract
Thermal resistance and moisture management characteristics are important attributes of textile materials for the characterisation of their ability to provide thermal comfort. Nettle fibre consists of a hollow core that is expected to enable good thermal and moisture regulation properties. Nonwoven fabrics of three different mass per unit area values, made from nettle, polyester and blends thereof, were prepared on a needle-punching machine, maintaining the same punch density and depth of penetration. The thermal conductivity, water vapour permeability, water retention, wicking, moisture management, drying rate and air permeability of these fabrics were evaluated. Nonwoven fabric prepared with 100% nettle fibres exhibited good thermal conductivity, while polyester fabric demonstrated good thermal insulation. The nettle fibre fabric showed good water retention, drying rate and moisture management properties. On the other hand, polyester-enriched fabric exhibited good wicking behaviour.
Keywords: Himalayan nettle, needle-punching, thermal insulation, wicking, moisture management, Girardinia diversifolia

## *Izvleček*
*Toplotni upor in prenos vlage sta pomembni lastnosti tekstilij za zagotavljanje toplotnega udobja. Vlakno iz koprive ima votlo jedro (lumen), ki naj bi tekstilijam zagotovilo dobro toplotno izolacijo in uravnavanje vlage. Iz vlaken koprive, poliestrskih vlaken in njihove mešanice so bile izdelane iglane vlaknovine s tremi različnimi ploščinskimi masami in enako gostoto iglanja ter enako globino penetracije igel. Ocenjeni so bili toplotna prevodnost, prepustnost vodne pare, zadrževanje vode, kapilarni prenos vlage, celoten prenos vlage, hitrost sušenja in zračna prepustnost. Vlaknovina iz 100-odstotnih vlaken koprive se je odlikovala po dobri toplotni prevodnosti, vlaknovina iz poliestrskih vlaken pa po dobri toplotni izolativnosti. Vlaknovina iz vlaken koprive je dobro zadrževala vodo, se hitro sušila in imela dober celoten prenos vlage. Vlaknovina iz mešanice vlaken koprive in poliestrskih vlaken je dobro prenašala kapilarno vlago.*
*Ključne besede: himalajska kopriva, iglanje, toplotna izolacija, kapilarni prenos vlage, prenos vlage, Girardinia diversifolia*

## 1 Introduction

Nettle fibre is a cellulose fibre with a long and fascinating history that can be traced back to the Bronze Age, when it was used to make cloth. Probably the best-known find is from the Danish Voldtofte grave, where nettle cloth was used to wrap human bones, and dates back to between 900 and 750 BC [1]. Several species

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of the nettle family (*Urticaceae*) are known today and are used to produce bast fibres similar to flax. Many of those species have been used to produce fibre for making textiles and clothing for thousands of years. There are two main species of the fibre: European nettle (or stinging nettle) and Himalayan nettle. European nettle is difficult to grow commercially. Himalayan nettle (*Girardinia diversifolia*) is a large nettle grown mainly in the Himalayan region, in areas such as tropical Africa (from Ethiopia to Madagascar), and in Yemen, Nepal, India, Sri Lanka, southern China, Taiwan and Indonesia [2–4]. In all of these species, the fibre comes from the stem and, incidentally, there is no sting left in the extracted fibre. The plant grows from 1 to 3 meters in height. The physical and tensile properties of the Himalayan nettle fibre is reported to be better than other high-strength bast fibre such as flax, hemp and ramie, as shown in Table 1 [4]. Nettle fibre is thus used for a wide range of applications, as shown in Table 2.

The fibres contain 48% cellulose, which is much lower than that of ramie and flax, in which the cellulose content is approximately 73% and 75%, respectively. Lignin and hemicellulose, which are considered to be useless and even harmful in textile processing, should be removed through degumming. After degumming, the fibre contains 11% moisture, 67% cellulose, 8% hemicellulose, 4% lignin and 3% ash [2]. The fibre is used to spin durable yarns from which nets, ropes and fishing nets are traditionally made [3]. The fibre is blended with other natural and synthetic fibres spin yarns to make dresses, jackets, scarves and shawls. Because nettle fibre is hollow, it is used to produce a composite that helps to improve vibration absorption capacity [5]. Thermal insulation is one of the desirable attributes of textiles. It is important for assessing apparel comfort for the user. In addition to thermal insulation, moisture management is also one of the key performance criteria in today's apparel industry and influences the comfort level of the wearer. Apparel manufacturers have shifted their attention to the high-performance end of the moisture management fabric market, while the performance of garments is of increasing importance to consumers.

In recent times, a wide range of textile materials has been used as thermal insulators in many industrial applications, such as the insulation of buildings, boilers, chimneys, furnaces, etc. [6–7]. The thermal insulating properties of textile fabrics depend on their thermal resistance, porosity and thickness. One major hazard that synthetic fibres pose to the environment is their non-biodegradability. On the other hand, most natural fibres are biodegradable and sustainable, provided that eco-friendly techniques are employed in every stage of their production and disposal. In the natural fibre

*Table 1: Average physical and tensile properties and the associated standard deviation of single nettle fibre compared with other bast fibres [4]*

| Fibre | Length [mm] | Area of cross section [μm$^2$] | Breaking extension [%] | Young modulus [GPa] |
|---|---|---|---|---|
| Himalayan nettle fibre (*G. diversifolia*) | 478 ± 21 | 479 ± 186 | 6.2 ± 1.3 | 73 ± 22 |
| Flax | 27 ± 3 | 183 ± 87 | 3.3 ± 0.4 | 54 ± 15 |
| Hemp | 20 ± 5 | 764 ± 260 | 0.8 ± 0.1 | 19 ± 4 |
| Ramie | 135 ± 15 | 270 ± 93 | 2.5 | 24.5 |

*Table 2. Products produced from various parts of the nettle plant*

| Material | Uses |
|---|---|
| Long bast fibre of exceptional strength | Textile manufacturers |
| Wood fibres | Paper making |
| Leavulose | Sugar that can be used in food |
| Chlorophyll | Medicinal purposes |
| Powdered leaves | Cattle feed |

sector, environmental concerns have prompted the search for substitute textiles to replace cotton. In recent years, a great deal of research has been conducted to develop environmentally friendly textiles that are economically viable. Hemp, flax and stinging nettle have all received considerable attention. Both hemp and flax produce coarser fibres than nettle, resulting in a strong but rather rough fabric [8]. Although these fibres are unable to replace cotton, nettle has emerged as a substitute for other natural fibres, such as jute and flax, due to its distinguishing attributes [9]. To provide a viable alternative to textile fibre, it is necessary to extract the fibres from nettle plant efficiently and profitably. Nettle fibre loft, i.e. the amount of air entrapped by the fibrous structure is, similar to that of cotton [10]. Nettle is stronger, finer and more flexible than linen [10–12]. This indicates that eco-friendly clothing made from nettle will be more durable and of better quality. Nettle fibre morphology is similar to that of cotton, with a lumen in the middle of a kidney-shaped cross section [11]. Its surface has grooves that increase the fibre's surface area [11, 13]. This hollow core may be useful in creating fabrics for both warm and cold conditions. Nettle fibre has been reported to show excellent moisture management properties [14–16]. There is little information available in literature about the thermal and physiological comfort of textile fabrics made of nettle fibre. This fibre must therefore be studied for its use in thermal insulation, and in terms of physiological comfort. In this study, needle-punched nonwoven fabrics were prepared from polyester and nettle fibres for the purpose of assessing their thermal insulation and moisture management properties for potential applications in both the apparel and industrial sectors.

## 2 Materials and methods

### 2.1 Materials

Nettle and polyester staple fibres were used for the preparation of nonwoven samples. Polyester fibres of 1.67 dtex and a cut length of 80 mm were procured from Reliance Industries, India. Himalayan nettle fibres of 1.38 dtex and a cut length of 100 mm were purchased from Uttrakhand Bamboo Research Corporation, Dehradun, India. A total of nine needle-punched nonwoven fabrics with three different mass per unit area values were prepared using these nettle and polyester fibres, as shown in Table 3.

*Table 3. Data regarding prepared nonwoven samples*

| Fibre | Mass per unit area [g/m²] | | |
|---|---|---|---|
| Nettle | 75 | 125 | 175 |
| Nettle/polyester (N/P) blend (80:20) | 75 | 125 | 175 |
| Polyester | 75 | 125 | 175 |

### 2.2 Preparation of needle-punched nonwoven fabrics

The samples were prepared on a DILO needle-punch nonwoven machine at IIT Delhi, India. The parallel laid nonwoven samples of the above-stated mass per unit area were prepared by varying the feed of the web. A punch density of 100 needles/cm$^2$ and a penetration depth of 10 mm were maintained while giving two passages in a needle loom.

### 2.3 Measurement of porosity and air permeability

The porosity of the prepared samples was determined by measuring the total volume of fabric and calculating the total volume of fibre in the sample. The difference between these two values is deemed air space and when it is calculated as a percentage of the total volume, it is referred to as the void fraction or porosity of the fabric. This can be calculated using equation 1 below:

Porosity =

$$= 1 - \frac{\text{Density of fabric}}{\text{Average density of constituent fibres}} (\%) \quad (1).$$

Air permeability (cm$^3$cm$^2$s$^{-1}$) was measured using an FX 3300 Labortester III (Textest Instruments) air permeability tester according to BS 6636 standard.

### 2.4 Measurement of thermal conductivity

The thermal conductivity of the samples was measured using a thermal conductivity tester fabricated (Figure 1) by the Department of Textile Technology, NIT Jalandhar, India [17]. The instrument was fabricated according to the guidelines of the ASTM C518-10 standard for the measurement of the thermal conductivity of high-loft thick fibrous material, where the simulated measurement conditions were exactly the same as application conditions. The thermal conductivity tester consisted of a top hot plate ($\varphi$ = 20 cm) and a bottom cold plate ($\varphi$ = 20 cm) between which the sample was mounted. The distance between top and bottom plate was adjustable according to sample thickness. The temperature of the top plate can be raised from room temperature to 100 °C, while the temperature of the bottom plate can be reduced from room temperature to 0 °C. The temperature of both plates was monitored by circulating water to the container of the plates. The temperature difference between top and bottom plates was measured using an attached chromel-alumel thermocouple, while heat flow across the sample was measured using a heat flux sensor (Captec, France). The temperature of the top plate was kept fixed at 37 °C (average temperature of the human body core), while the temperature of the bottom plate was varied from room temperature to 0 °C to achieve different temperature differences to simulate variations in environmental temperature. After mounting the sample in the tester, the heat flux sensor was positioned under the sample at the centre. After that, about 20 minutes was required to achieve a steady state heat flow. The output signals of the heat flux sensor ($q/A$) and thermocouple ($\Delta T$) were recorded using a micro-voltmeter and converted to actual units using conversion charts. The thermal conductivities of the samples were calculated using Fourier's law, as given in equation 2:

$$k = \frac{q}{A} \times \frac{s}{\Delta T} \quad (2),$$

where, $k$ is the thermal conductivity of the fabric ($Wm^{-1}K^{-1}$), $q/A$ is the heat flux through the fabric ($W/m^2$), $s$ is the thickness of the fabric (m) and $\Delta T$ is the temperature difference (°C).
Thermal resistance was calculated using equation 3:

Thermal resistance =

$$= \frac{\text{Thickness}}{\text{Thermal conductivity}} \ (m^2K/W) \quad (3).$$

The thickness of the sample was calculated using a digital thickness tester (TESTEX Instrument ltd., China).

## 2.5 Measurement of water retention

The water retention of a fabric was measured by cutting 10 cm × 10 samples. First, the oven dry weight of the samples was measured after drying them at 105 °C for 180 hours inside an oven dryer. The samples were then immersed in deionised water for 30 minutes and hung for 10 minutes in a laboratory room at 22 °C and 65% relative humidity for the removal of excess water. Next, the weight of the samples was measured and the water retention capacity was calculated using equation 4:

Water retention =

$$= \frac{\text{Wet weight (g)} - \text{Oven dry weight (g)}}{\text{Oven dry weight (g)}} \times 100\ (\%) \quad (4).$$

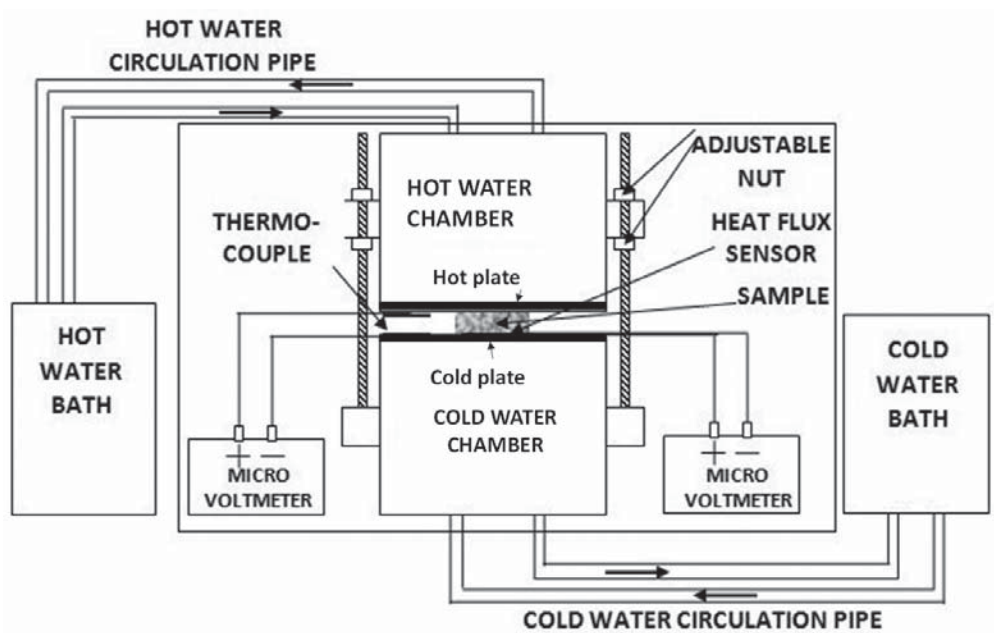



*Figure 1: Schematic diagram of thermal conductivity tester*

### 2.6 Measurement of wicking behaviour

An experimental set-up was prepared for the measurement of wicking behaviour, as shown in Figure 2. Specimens measuring 200 mm × 25 mm were cut. The bottom ends of the specimens were vertically immersed in water to a depth of 20 mm. A three-gram weight was affixed to the bottom end of each specimen. The wicking height versus time was observed for 15 minutes.

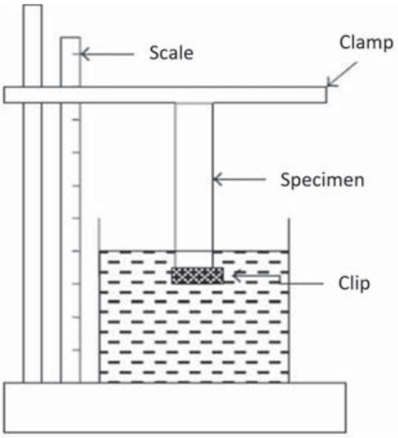



*Figure 2: Wicking tester*

### 2.7 Measurement of drying rate

The drying rate was defined using a drying rate tester (AL204). The standard applied for measurement purposes was AATCC 201. The sample size used was 15 cm × 15 cm. The test conditions used were a temperature of 22 °C ± 2 °C and a relative humidity of 66% ± 2%. The test sample was placed inside the weighing balance and 1 ml of deionised water was spread on top surface of the fabric. After measuring drying for 20 minutes, the instrument yielded the drying rate percentage of the sample.

### 2.8 Measurement of moisture vapour permeability

Moisture vapour permeability was measured using a water vapour permeability tester (SDL ATLAS M261) in accordance with the ASTM 1653-13 standard, as follows: an open cup containing water was sealed with a nonwoven fabric. The assembly was then placed in the test chamber at a controlled temperature of 20 °C ± 2 °C and a relative humidity of 65% ± 2%. The rate of water vapour loss was calculated by measuring the weight change of the cup containing the water after at least 1 hour. Moisture vapour permeability was calculated using equation 5:

$$\text{Moisture vapour permeability} = \frac{24\,M}{At}\,(\text{gm}^{-2}\text{day}^{-1}) \quad (5),$$

where, $M$ is water vapour loss expressed in the time period (g), $A$ is the area of the exposed specimen ($m^2$) and $t$ is time of exposure (h).

### 2.9 Measurement of moisture management properties

Moisture management properties were measured using a moisture management tester according to the AATCC 195 test standard. A sample size of 8 cm × 8 cm was used. The testing conditions used were a temperature of 22 °C ± 2 °C and a relative humidity of 66% ± 2%. The moisture management tester was used to spray water on the fabric surface for 20 seconds and then measured moisture management properties for 120 seconds. The moisture management tester measured the dynamic liquid transport properties of textiles in three dimensions. They were (i) wetting time: the moisture absorption time of the fabric's inner and outer surfaces; (ii) one-way transportation capability: liquid moisture one-way transfer from the fabric's inner surface to its outer surface; and (iii) spreading rate: the speed at which liquid moisture spreads on the fabric's inner and outer surface.

## 3 Results and discussion

### 3.1 Porosity and air permeability of nonwoven fabrics

A porous structure is required for air permeability, which relates to the comfort of textiles. A porous textile structure creates stationary air pockets that are ideal for good thermal insulation. A nonwoven

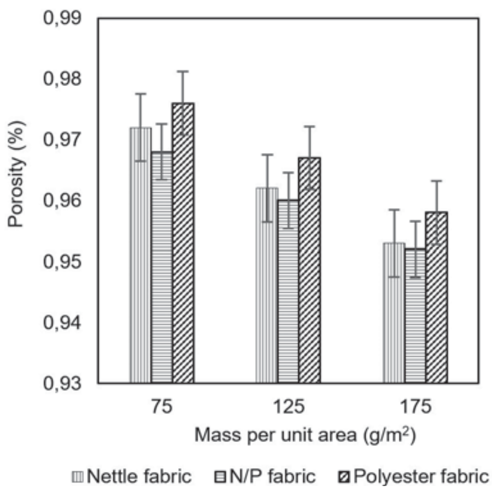



*Figure 3: Porosity of nonwoven fabrics*

structure is inherently porous, requiring the study of the porosity and air permeability of nonwoven fabric samples. The porosity and air permeability of all nonwoven fabrics were measured and the results are presented in Figure 3 and Table 4, respectively. It is evident from Figure 3 that polyester nonwoven fabrics have the highest porosity, followed by 100% nettle and N/P blended nonwoven fabrics, while the air permeability of polyester nonwoven fabric was the lowest. This may be due to the presence of small and uniform-sized pores in a larger numbers in polyester nonwoven fabrics, creating stationary air pockets that restricted heat flow.

*Table 4: Air permeability of the nonwoven fabrics*

| Fabric composition | Air permeability a) [cm$^3$ cm$^{-2}$s$^{-1}$] | | |
|---|---|---|---|
| | 75 g/m$^2$ | 125 g/m$^2$ | 175 g/m$^2$ |
| Nettle | 206.7 ± 6.2 | 158.8 ± 4.2 | 139.2 ± 4.1 |
| N/P | 211.6 ± 6.3 | 167.3 ± 3.9 | 142.6 ± 4.2 |
| Polyester | 174.8 ± 4.5 | 136.3 ± 3.2 | 88.6 ± 2.3 |

a) Average value and the associated ± 95% confidence interval

## 3.2 Thermal conductivity of nonwoven fabrics

The thermal conductivity of all the samples was measured 20 times in repeated tests. The average thermal conductivity of the samples is shown in Table 5. For the same types of fabrics, an increase in mass per unit area results in a decrease in thermal conductivity and an increase in thermal resistance, as shown in Figures 4 and 5. However, the thermal conductivity of the fabrics decreases as the polyester content increases. This was found to be lowest in the case of 100% polyester nonwoven. For the same mass per unit area, polyester nonwoven fabrics comprise a higher number of fibres, producing a thicker fabric. As thickness increases, thermal resistance increases. The result is the better thermal resistance of polyester nonwoven fabric compared with nettle fibre nonwoven fabric. The thermal resistance of a nonwoven structure is influenced by its structural compactness with optimum porosity [17]. A good

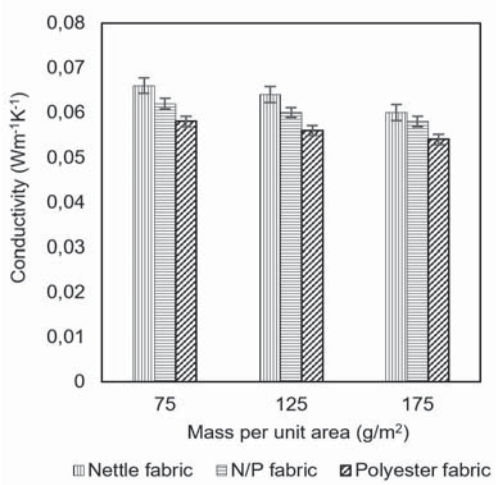



*Figure 4: Thermal conductivity of nonwoven fabrics*

*Table 5: Thermal conductivity, thickness and thermal resistivity of nonwoven fabrics*

| Fabric composition | Mass per unit area a) [g/m$^2$] | Thermal conductivity a) [Wm$^{-1}$K$^{-1}$] | Thickness a) [mm] | Thermal resistance [m$^2$K/W] |
|---|---|---|---|---|
| Nettle | 75 ± 3 | 0.066 ± 0.002 | 1.65 ± 0.11 | 0.025 |
| | 125 ± 5 | 0.064 ± 0.002 | 2.21 ± 0.12 | 0.035 |
| | 175 ± 6 | 0.060 ± 0.002 | 2.54 ± 0.12 | 0.042 |
| Nettle/polyester (N/P) blend (80:20) | 75 ± 3 | 0.062 ± 0.002 | 1.58 ± 0.11 | 0.025 |
| | 125 ± 6 | 0.060 ± 0.002 | 2.11 ± 0.11 | 0.035 |
| | 175 ± 6 | 0.058 ± 0.002 | 2.45 ± 0.13 | 0.042 |
| Polyester | 75 ± 2 | 0.058 ± 0.001 | 2.02 ± 0.13 | 0.035 |
| | 125 ± 3 | 0.056 ± 0.001 | 2.38 ± 0.15 | 0.043 |
| | 175 ± 4 | 0.054 ± 0.001 | 2.80 ± 0.14 | 0.052 |

a) Average value and the associated ± 95% confidence interval

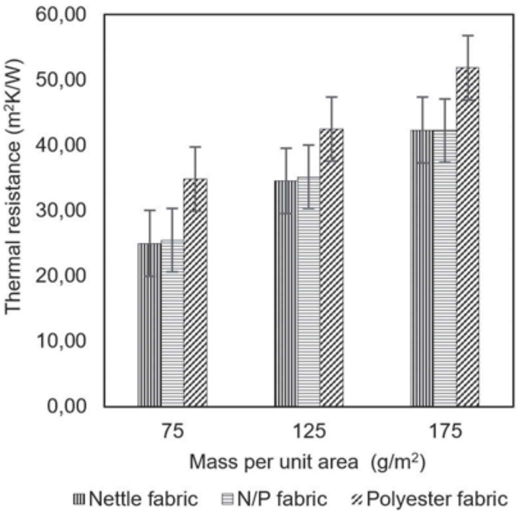



*Figure 5: Thermal resistance of nonwoven fabrics*

statistical correlation ($r$ = 0.76) between thermal conductivity and porosity of nonwoven samples was identified.

## 3.3 Moisture vapour permeability

Moisture vapour permeability is defined as the ability of a textile material to allow water vapour to pass through it. How water in a gaseous form (vapour) passes through a material is influenced by pore size and the distribution of pores in the material. It was observed that moisture vapour permeability (Figure 6) decreased with an increase in mass per unit area. As mass per unit area increased, the fabrics became thicker and, as a result, the size of the pores

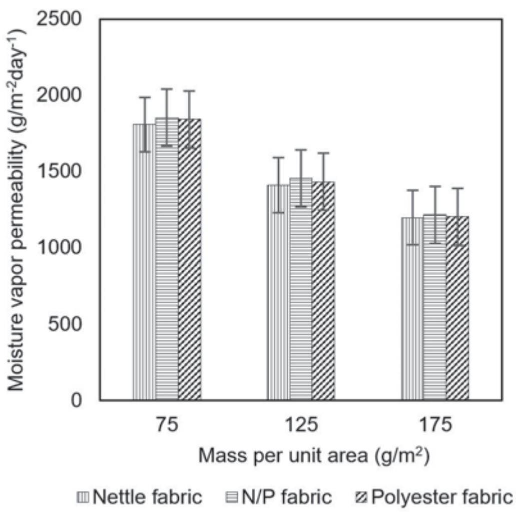



*Figure 6: Moisture vapor permeability of nonwoven fabrics*

decreased, which restricted the flow of moisture vapour across the thicker fabric structure. However, the moisture vapour permeability of all the three fabrics was similar and the differences were not statistically significant.

## 3.4 Water retention

The average water retention capacity of the nonwoven samples was measured and plotted, as shown in Figure 7. The water retention capacity of nettle fibre nonwoven fabric was found to be highest due to its hydrophilic nature. The water retention capacity increased with an increase in the mass per unit area of nettle and N/P blended nonwoven fabrics, while no significant difference was observed in the water retention capacity of various 100% polyester nonwoven fabrics. In the case of 75 g/m² nettle and N/P blended fabrics, no significant difference in water retention capacity was observed. This may have been due to the presence of hydrophobic polyester fibres and the thinner structure of the fabrics, allowing for the removal of moisture across the thickness in a similar way.

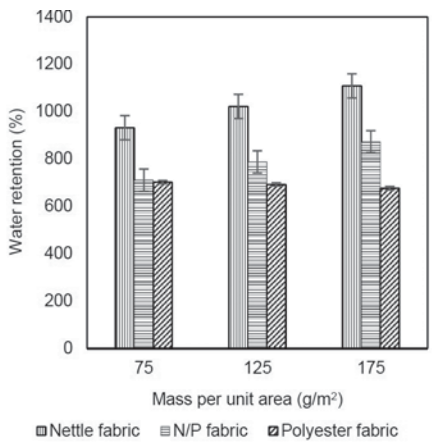



*Figure 7: Water retention capacity of nonwoven fabrics*

## 3.5 Wicking behaviour

Wicking behaviour is defined as the performance of fabric, which facilitates the movement of moisture away from the surface. It works by absorbing and spreading moisture out across the fabric to enhance the evaporative drying rate. The results of wicking height measured using the experimental set-up (as discussed in the experimental section) is shown in Figure 8. Figure 8 shows that the polyester nonwoven fabric demonstrated excellent wicking property compared with nettle. Wicking efficiency increased with

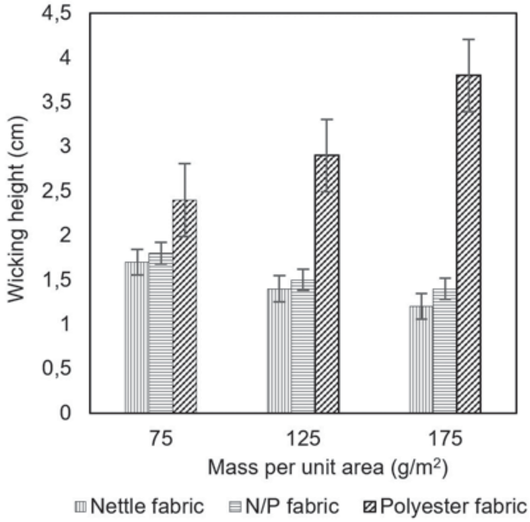



*Figure 8: Wicking behaviour of nonwoven fabrics*

an increase in the mass per unit area of the polyester nonwoven fabrics. In the case of nettle and nettle-polyester nonwoven fabrics, wicking efficiency decreased with an increase in mass per unit area. The hydrophobic nature of polyester did not result in any absorption and facilitated the transfer of moisture. In the case of nettle and nettle-polyester nonwoven fabrics, moisture was absorbed by the fibres instead of being transferred due to the hydrophilic nature of fibre. In the case of N/P blended nonwoven fabric (80/20), the polyester fibre content is only 20% that is solely responsible for wicking. As a result, nettle fibre was a significant factor for the poor performance demonstrated by blended nonwoven fabrics. Moreover, the difference in the mechanical properties of the two fibres does not facilitate a close association to form a uniform structure after needle-punching. This led to a variation in the inter-fibre spacing, leading to the inefficient transfer of liquid through wicking.

## 3.6 Moisture management properties

Moisture management behaviour describes the ability of fabric to regulate the transmission of moisture. The moisture management properties were evaluated through the assessment of (a) top and bottom wetting time, (b) top and bottom absorption rate, (c) top and bottom spreading (mm/s) and (d) overall moisture management capacity.

### 3.6.1 Top and bottom wetting time

Top and bottom wetting time is the time period in which the top and bottom surfaces of a fabric just begin to become wetted [18]. It evident from Figure 9a and Figure 9b that both the top and bottom wetting time of blended nonwoven fabrics was significantly higher than either the 100% nettle or the 100% polyester nonwovens fabrics.

The top and bottom wetting time of a fabric depends on its affinity to liquid and on the amount of available space in the structure for the movement of a liquid. Nettle fibre is hydrophilic in nature, so it quickly absorbs water and demonstrates a shorter wetting time (top and bottom). In the case of polyester nonwoven fabric, polyester fibre has the ability of the quick dispersion of water supported by wicking, even though the fabric is hydrophobic in nature. For this reason, its wetting time is the shortest. The nettle/polyester blend demonstrated the highest wetting time due to its two contradictory behaviours of water absorption and transfer.

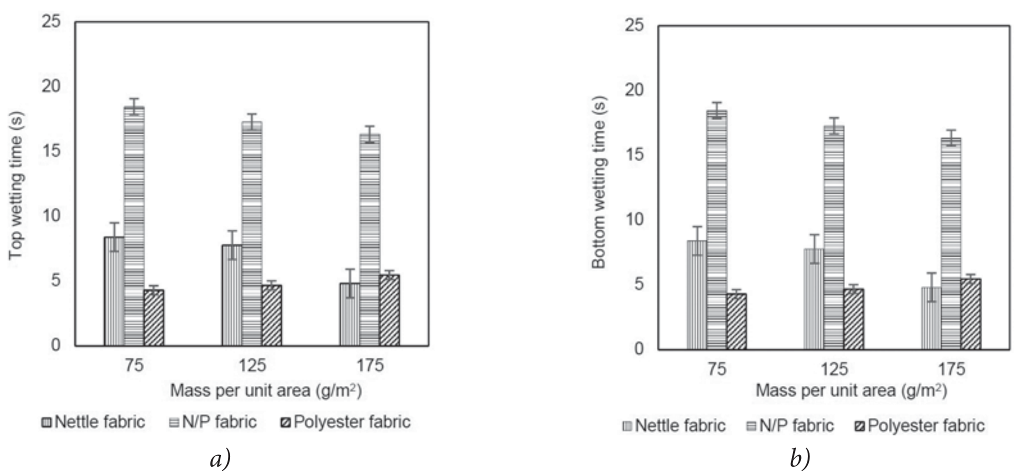
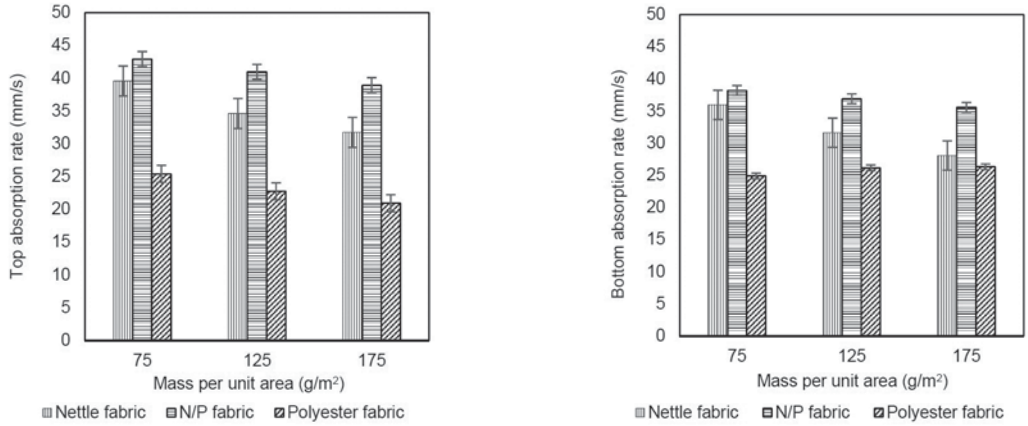



*Figure 9: Wetting time of nonwoven fabrics: a) top and b) bottom*




*a)* *b)*

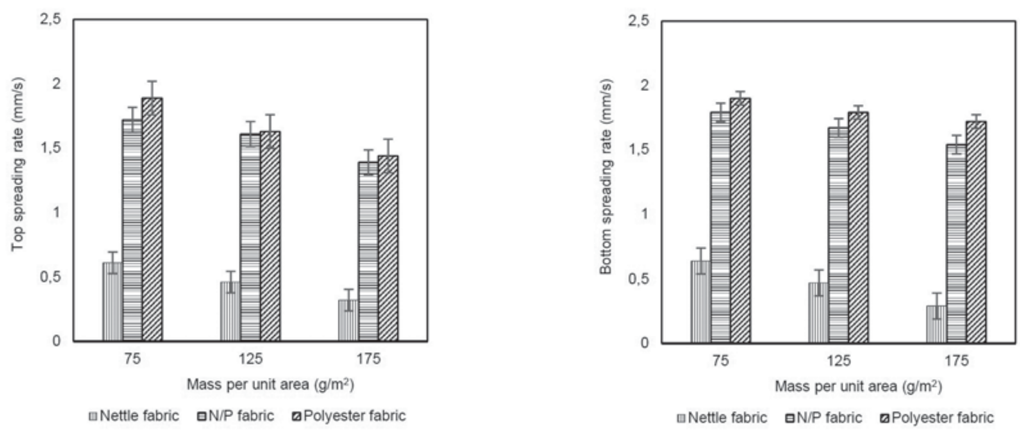
*Figure 10: Effect of mass per unit area: a) on top absorption rate and b) on bottom absorption rate*

### *3.6.2 Top and bottom absorption rate*

The top and bottom absorption of liquid by a textile substrate indicates the degree of transfer of liquid on its surface. The absorption of liquid by a fabric is influenced by the type of fibre, fabric structure and porosity of the structure [18]. It is evident that the top and bottom absorption rate (Figure 10) is highest in case of blended fabrics. The absorption rate depends on the porosity of the fabric. As the mass per unit area increases, the top and bottom absorption rate decreases due to a decrement in porosity with an increment in mass per unit area. Exceptional trans-planar behaviour was identified for nettle/polyester blended fabric. This might be the result of better wicking due to better micro-capillary action.

### *3.6.3 Top spreading and bottom spreading*

Spreading speed refers to the ability of a fabric to allow liquid to move outward across its plane. A fibre with a lower liquid holding capacity will allow such trans-planar movement [18]. The top and bottom spreading behaviour of the nonwoven fabrics is shown in Figure 11. Both top and bottom spreading rates were the slowest in the case of 100% nettle nonwoven fabric. The presence of polyester fibre in the nonwoven fabrics significantly accelerated the spreading of water. This is due to hydrophobic nature of the polyester fibre attributable to the pronounced capillary effect, which facilitates the adsorption of water molecules on the surface of the fibres and the spreading of the same at a faster rate without absorption. Hydrophilic nettle fibre absorbs water quickly,




*a)* *b)*

*Figure 11: Effect of mass per unit area: a) on top spreading and (b) on bottom spreading*

which limits the spreading of water on the surface. The top and bottom spreading speed decreased with an increase in mass per unit area due to the presence of nettle fibres that can absorb moisture.

### 3.6.4 Overall moisture management capacity

Overall moisture management capacity is an index that indicates the overall ability of a fabric to manage the transport of liquid moisture. This includes three aspects of performance, i.e. spreading speed or drying speed, the moisture absorption rate of the bottom side and one-way liquid transport ability. A higher overall moisture management capacity indicates the better overall moisture transportability of a fabric [18]. The overall moisture management capacity of fabrics is shown in Figure 12.

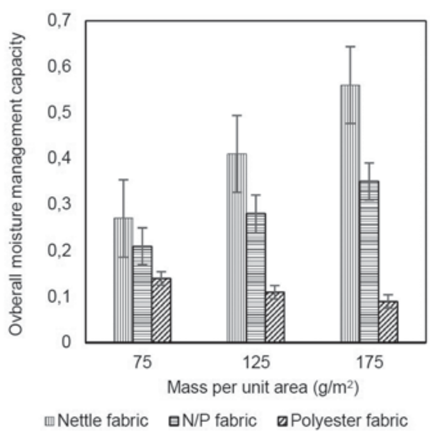



*Figure 12: Overall moisture management capacity of nonwoven fabrics*

It is evident from Figure 12 that overall moisture management capacity increases with an increase in nettle fibre content, as well as the mass per unit area of the nettle-enriched nonwoven fabrics, while overall moisture management capacity decreases with an increase in mass per unit area for 100% polyester fabric.

## 4 Conclusion

Needle-punched nonwoven fabrics with three different mass per unit area values (77 g/m$^2$, 125 g/m$^2$ and 175 g/m$^2$) of nettle, polyester and nettle polyester blend were prepared in a DILO needle-punched nonwoven machine, while maintaining the same levels of punch density and depth of penetration. It was determined that the preparation of a uniform nonwoven structure in terms of equal pore size from 100% nettle fibre is difficult, and that it would be easier if polyester fibres are blended with the nettle fibre. The polyester nonwoven fabric exhibited the best thermal resistance due to its structural uniformity, in terms of a large number of small and uniform pores, and its greater thickness. The polyester nonwoven fabrics also had the highest wicking rate, as their hydrophobic nature facilitated the capillary flow of the fibre. On the other hand, the nettle nonwoven fabrics demonstrated high water vapour and air permeability, and the best overall moisture management capacity and water retention properties. Thus, nettle fibre nonwoven fabrics, as biodegradable and sustainable material, could serve as an alternative for various industrial and household applications. In recent years, organisations such as the European Union and the Interactive European Network for Industrial Crops and their Applications (IENICA) have been encouraging scientists to develop environmentally friendly textiles from natural fibres, such as jute, hemp, flax, etc. that are economically viable. Nettle fibre is also garnering considerable attention due to the promising attributes discussed in this article. Although nettle is unable to replace cotton, it may emerge as a substitute for synthetic and other natural fibres due to its distinguishing attributes.

However, the behaviour of the nettle fibre may become softer, similar to cotton to a certain extent, after lignin is removed from its surface. Its hollow structure and antimicrobial property (with lignin) can be studied in more detail in the future in order to find suitable applications of this fibre in practical use.

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