Journal of Textile Science and Technology, 2026, 12(2), 43-54
https://www.scirp.org/journal/jtst
ISSN Online: 2379-1551
ISSN Print: 2379-1543

# Effect of Raising Waste Content on the Mechanical and Thermophysiological Performance of Needle-Punched Nonwoven Surfaces and the Application of Biomimetic Printing

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**How to cite this paper:** Öztürk, R.Z.G. (2026) Effect of Raising Waste Content on the Mechanical and Thermophysiological Performance of Needle-Punched Nonwoven Surfaces and the Application of Biomimetic Printing. *Journal of Textile Science and Technology*, **12**, 43-54.
https://doi.org/10.4236/jtst.2026.122004

**Received:** March 14, 2026
**Accepted:** April 24, 2026
**Published:** April 27, 2026

## Abstract

In this study, viscose/polyester blended raising waste generated during the textile raising process was evaluated through a recycling approach, and nonwoven surfaces were produced using the needle-punching method. Samples with three different blend ratios (P30R70 (30% polyester/70% raising waste), P50R50 (50% polyester/50% raising waste), and P70R30 (70% polyester/30% raising waste) and a control sample (P100 (100% polyester)), were prepared under identical needle-punching conditions. Biomimetic digital print designs derived from the porous calcium carbonate skeletal structures of fossilized marine corals, as well as their layered growth patterns and lattice-like organizations, were applied to the produced surfaces. The samples were comparatively evaluated in terms of tensile strength and elongation behavior, air permeability, thermal resistance, water vapor resistance, and post-printing color fastness. The results indicated that the P50R50 sample exhibited the highest strength and elongation values, while the P70R30 sample provided a favorable balance among permeability, thermal resistance, and moisture transfer. Post-printing fastness values indicated that the biomimetic printing application provided adequate performance for functional use.

## Keywords

Biomimetic Design, Raising Waste, Nonwoven Surface, Digital Disperse Printing, Comfort, Color Fastness

## 1. Introduction

Raising, one of the mechanical finishing processes in textile production, increases the perceived volume and comfort of a fabric by creating a brushed surface. However, the process also generates a considerable amount of short-fiber, heterogeneous waste. In particular, polyester/viscose blended raising waste constitutes a waste stream that is difficult to re-utilize in conventional yarn production processes because of its short fiber length and mixed structure. With the increasing scale of textile production, the volume of process-derived fiber waste has also grown, and the literature emphasizes that this issue should be addressed within the framework of circular economy strategies [1] [2]. For this reason, converting raising waste into high-value-added products is important both for improving resource efficiency and for reducing the carbon footprint.

Nonwoven technologies provide a strong production platform for the utilization of raising waste because short and heterogeneous fibers can be reorganized through mechanical bonding. Needle-punched nonwoven structures can provide sufficient mechanical integrity through the three-dimensional interlocking of fibers and are widely used in applications such as automotive interior trim, sound insulation, and structural interlayer materials.

Recent studies have demonstrated that recycled fiber-based nonwoven materials can be suitable for industrial applications in terms of technical performance [3] [4]. This approach presents a sustainable model by enabling waste materials to be transformed into functional technical products rather than being disposed of as low-value waste.

The distinctive aspect of this study is the integration of recycled nonwoven surface development with biomimetic surface design. The biomimetic approach aims not only to imitate the formal characteristics of natural structures but also to transfer their formation principles and structural organization into design. In recent years, bio-design-based material development approaches have been identified as offering an interdisciplinary methodology for sustainable innovation [5] [6]. The porous calcium carbonate skeletal structures of marine corals, their layered growth organization, and the balance between void and solid were examined and transformed into parametric pattern designs. By establishing a conceptual correspondence between the hierarchical pore distribution of coral structures and the topology of the nonwoven fiber network, a relationship was created between the structural character of the material and the surface pattern. The developed biomimetic patterns were applied to nonwoven surfaces obtained from raising waste with different blend ratios using digital disperse printing technology. Digital printing techniques are known to provide advantages for sustainable textile production because of their low water consumption, flexible pattern generation, and controllable chemical usage [7].

This study aims to propose an approach for sustainable technical textile production through the integration of nonwoven recycling of raising waste, biomimetic pattern design, and digital printing technology.

## 2. Materials and Method

### 2.1. Materials

The properties of the raising waste fibers and polyester fibers are presented in Table 1.

**Fiber Composition and Nonwoven Production**

Raising waste consisted of 85% polyester and 15% viscose fibers, while virgin polyester was used as the support fiber. All waste materials used in the study were obtained from the same production batch in order to ensure consistency and reproducibility of the results. The fineness and lengths of the fibers are presented in Table 1.

Table 1. Properties of raising machine waste and polyester fibers.

| Materials | Waste percentage (%) | Fiber diameter (dtex) | Fiber length (mm) |
|---|---|---|---|
| Raising machine waste polyester fiber | 85 | 2 | 22 |
| Raising machine waste viscose fiber | 15 | 2,2 | 17 |
| Polyester fiber | - | 3,3 | 50 |

### 2.2. Preparation of Nonwovens

Raising machine waste was blended with polyester fibers, and needle-punched nonwoven samples were produced at the Istanbul Textile Exporters' Associations Innovation Center (ITHIB Innovation Center, Istanbul). The parameters of the sample production process are presented in Table 2. The production line consisted of a carding machine (CFS1; feeding width/exit: 1000 mm; 650 m/min), a cross-laying machine (FRT50; input/output: 1000 mm; band speed: 49 m/min; exit speed: 6 m/min), and a needling machine (MAG4000 roller AR95; pre-needling/end-needling width: 1200 mm; calender distance: 0 - 10 mm; roller width: 1200 mm; needling speed: 0 - 400 rpm; oven speed: 0 - 6.5 m/min; roller speed: 0 - 10 m/min). The machine capacity was 50 kg/h, and the production width was 1000 mm (Cormatex S.R.L.). Blends of P100 (100% polyester), P30R70 (30% polyester/70% raising waste), P50R50 (50% polyester/50% raising waste), and P70R30 (70% polyester/30% raising waste) were prepared and fed into the carding machine. The formed webs were then oriented in the cross-machine direction using a cross lapper in order to obtain the required fabric mass per unit area.

Table 2. Production parameters of the nonwoven samples.

| Blend ratio used in the study | Mass per unit area (g/m$^2$) | Thickness (mm) | Punching density (punch/cm$^2$) |
|---|---|---|---|
| P100 | 100 | 50 | 75 |
| P30R70 | 121 | 50 | 75 |
| P50R50 | 135 | 50 | 75 |
| P70R30 | 150 | 50 | 75 |

### 2.3. Biomimetic Pattern Development

In this study, the biomimetic pattern approach was structured as a design strategy grounded in environmental awareness, with the aim of supporting the sustainable utilization of raising waste. The pattern concept was developed by establishing a relationship between the pore organization of coral skeletal structures and the fiber network morphology of nonwoven surfaces. Within the biomimetic design framework, the porous nonwoven structure produced from recycled raising waste was associated with the permeable morphology of coral structures. Thus, the approach was considered not only as an aesthetic reference but also as a process of sustainable material development (**Figure 1**).

**Figure 1.** Corals used in the biomimetic-inspired pattern study [8].

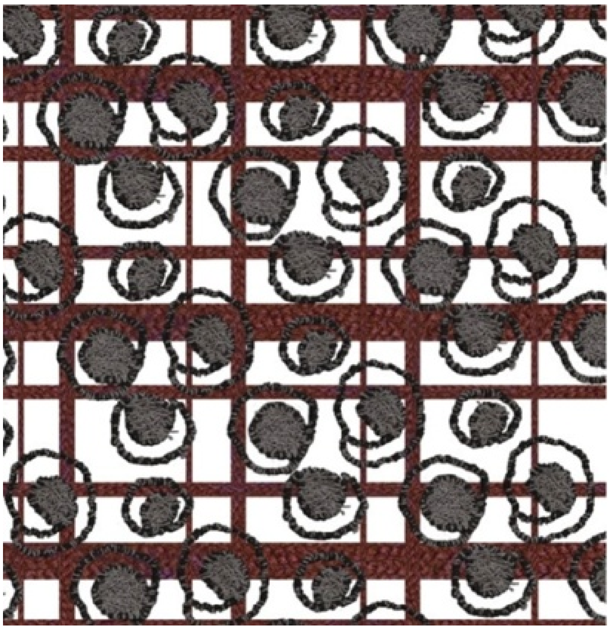


**Figure 2.** Pattern interpretation derived from corals.

The extinction process of corals was metaphorically represented in the pattern through a reduction in color intensity and an increase in the proportion of void spaces. In this way, the design conveys both an environmental message and an emphasis on the use of recycled materials. Within this framework of sustainability awareness, the pattern shown in **Figure 2** was applied as a print design to non-woven surfaces produced from raising waste/polyester blends.

## 2.4. Digital Disperse Printing

Digital inkjet disperse printing was applied to the nonwoven surfaces. Prior to printing, the samples were conditioned at 20˚C ± 2˚C and 65% ± 2% relative humidity. Light calendaring was applied to ensure surface uniformity. A piezoelectric inkjet printing machine was used in the printing process.

The digital disperse printing application was carried out in accordance with the chemical and process parameters presented in **Table 3** in order to optimize dye penetration and fastness performance on polyester-based nonwoven surfaces.

**Table 3.** Chemical and process parameters for digital disperse printing.

| Process stage | Chemicals | Concentration |
|---|---|---|
| Pre-treatment | Non-ionic wetting agent | 1 - 2 g/L |
| | Dispersion stabilizer | 2 - 3 g/L |
| | pH adjustment | 6.0 - 6.5 |
| Printing Ink | Disperse dye | 3% - 5% (w/v) |
| | Glycol-based humectant | 5% - 10% |
| | Deionized water | Remaining amount |
| Printing Parameters | Drop Volume | 6 - 12 pL |
| | Resolution | 600 - 1200 dpi |
| | Number of passes | 1 |
| Thermal Fixation | Temperature | 180˚C |
| | Time | 60 seconds |
| Cooling | Ambient temperature | 20˚C - 25˚C |

## 2.5. Test Methods

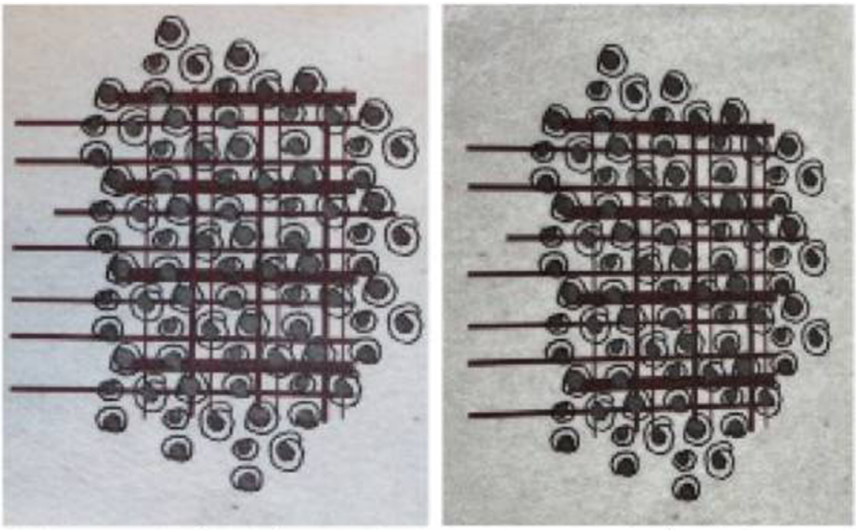
All samples produced in the experimental study were conditioned for 24 hours under standard atmospheric conditions (20˚C ± 2˚C and 65% ± 2% relative humidity) prior to testing. The mass per unit area of the samples was determined in accordance with the EDANA ERT 40.3-1990 standard. Thickness measurements were carried out according to the EDANA ERT 30.5-1999 standard using an SDL Atlas M034A Digital Thickness Tester operating under a pressure of 1 kPa. The tensile strength and elongation values of the samples in the machine direction (MD) were measured using an Instron 4410 universal testing machine in accordance with EN ISO 13934-1.

For the evaluation of thermophysiological performance, air permeability tests were conducted in accordance with TS EN ISO 9237, and the results were reported in L/m$^2$/s. The water vapor resistance (Ret) and thermal resistance (Rct) values of the samples were measured according to TS EN ISO 11092, with all measurements performed under controlled laboratory conditions. All mechanical and thermophysiological tests were performed on unprinted samples in order to evaluate the intrinsic material properties without the influence of printing. Within the scope of post-printing color fastness evaluation, washing fastness was assessed according to ISO 105-C06, rubbing fastness according to ISO 105-X12, and light fastness according to ISO 105-B02. All tests were carried out under standard atmospheric conditions, and average values were calculated based on at least three repetitions for each sample.

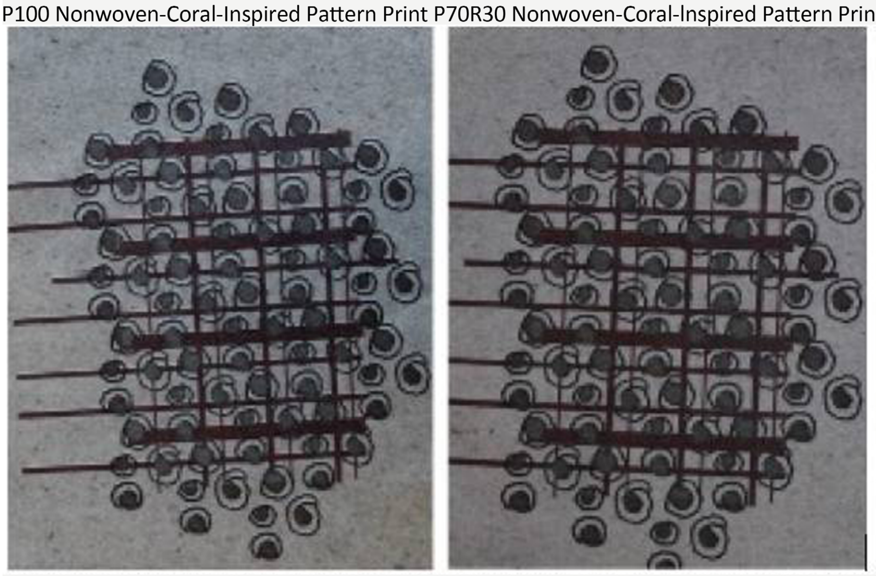
## 3. Results and Discussion

### 3.1. Digital Printing Results

Digital inkjet disperse printing was applied to **nonwoven surfaces composed of raising waste with different blend ratios**. The printed images of the coral-inspired pattern interpretations are presented in Figure 3.



P100 Nonwoven-Coral-Inspired Pattern Print P70R30 Nonwoven-Coral-Inspired Pattern Print



P50R50 Nonwoven-Coral-Inspired Pattern Print P30R70 Nonwoven-Coral-Inspired Pattern Print

Figure 3. Nonwoven surfaces featuring digitally printed coral pattern interpretations.

## 3.2. Mechanical Properties

The tensile strength results (**Figure 4**) indicate a significant increase in strength for all blends containing raising waste compared with the pure polyester sample. The machine direction (MD) tensile strength of the 100% polyester sample increased from 100.9 N to 305.7 N in the 50% raising waste/50% polyester blend. In the cross direction (CD), the highest value, 241.4 N, was obtained for the 30% raising waste blend. This increase is attributed to greater fiber entanglement during the needle-punching process and to the increase in basis weight, which enlarges the load-bearing fiber cross-sectional area. The literature also indicates that intermediate blend ratios in hybrid fiber systems can provide favorable mechanical performance [9] [10]. However, increasing the raising waste ratio to 70% resulted in a noticeable decrease in CD strength (146.6 N). This decrease can be explained by irregularities in fiber orientation and the increased proportion of short fibers. Overall, the 50/50 blend ratio provided the most balanced performance in terms of bidirectional strength, demonstrating that recycled fibers can be structurally suitable for technical nonwoven applications.

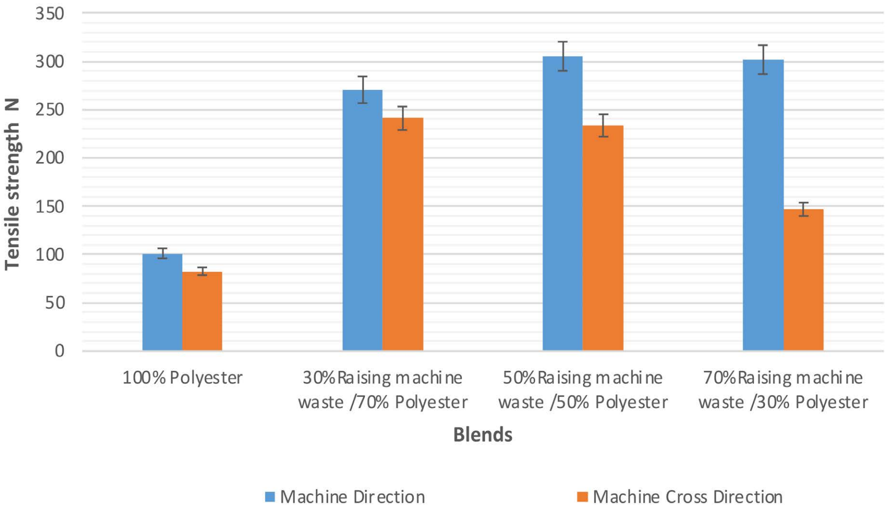


**Figure 4.** Tensile strength values (N) according to blend ratios.

When the elongation results are evaluated (**Figure 5**), the addition of raising waste is observed to increase the deformation capacity of the nonwoven structures. The elongation value in the machine direction (MD), which was 71.8% for the 100% polyester sample, increased to 88.2% in the 30% raising waste/70% polyester blend and was 84.3% in the 50/50 blend. This increase is attributed to the repositioning of fibers under load within the nonwoven structure and to the increase in energy absorption through inter-fiber friction mechanisms. However, when the raising waste ratio increased to 70%, the elongation in the cross direction (CD) decreased to 58%. This reduction is associated with the higher proportion of short fibers, which leads to reduced fiber continuity and earlier failure during load transfer. The literature also indicates that the elongation behavior of needle-punched nonwoven structures is directly related to fiber length distribution, bonding density, and fiber orientation [11] [12]. Blend ratios containing 30% - 50% raising waste provide a more balanced performance in terms of ductility and structural integrity.

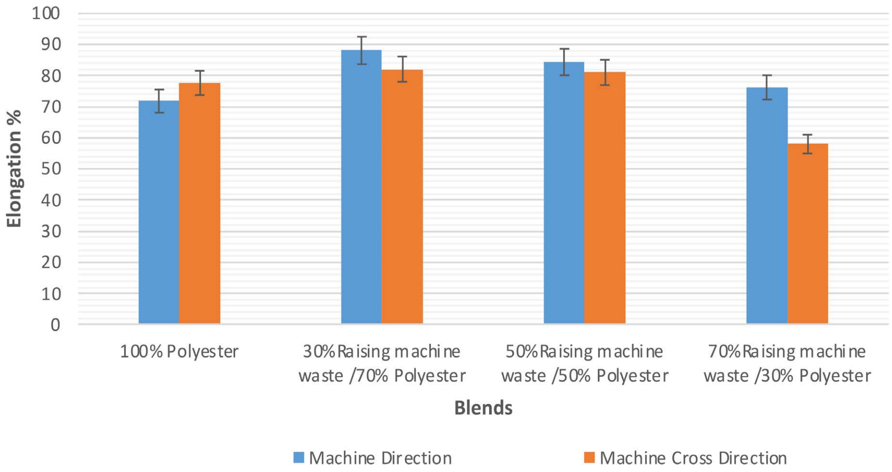


**Figure 5.** Elongation (%) values according to blend ratios.

### 3.3. Air Permeability Results

The air permeability results (**Figure 6**) show a clear increasing trend with the increase in the proportion of raising waste. While the sample containing 100% polyester exhibited the lowest air permeability value, the sample containing 70% raising waste reached the highest value. This result indicates that changes in fiber composition directly affect the porosity morphology of the nonwoven structure. Since raising waste consists of short and heterogeneous fibers, the fiber network formed after needle-punching exhibits a more irregular and open porous structure. The increase in pore volume reduces resistance to airflow, thereby increasing permeability. Increased thickness generally enhances resistance to airflow and heat transfer; however, in this study, the effect of increased porosity due to higher raising waste content was found to be more dominant. Since the thickness of all the samples was the same (**Table 2**), the change in the air permeability results can

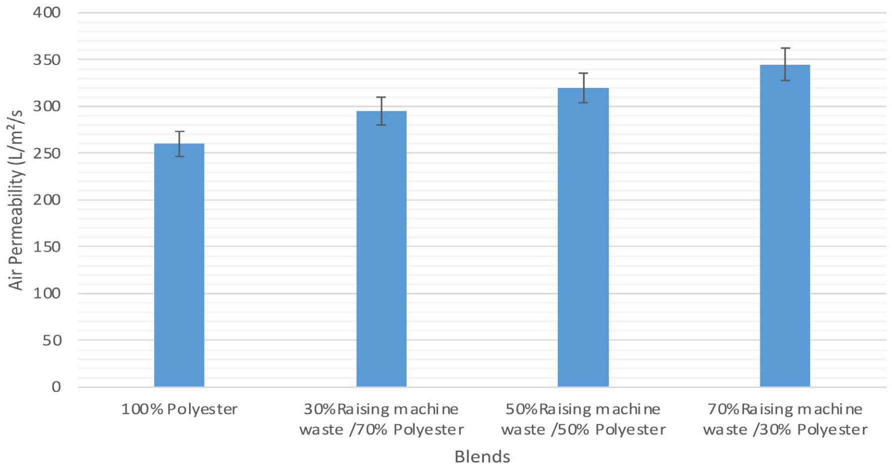


**Figure 6.** Air permeability values according to the blend ratios.

be explained by the change in the fiber composition ratio. The fiber composition of the nonwoven fabric samples consisted of different fiber diameters and fiber lengths, which mainly affect the air permeability through the change in the porosity of the fabric. This finding is consistent with studies reporting a strong and generally linear relationship between porosity and air permeability in nonwoven structures [13] [14]. Furthermore, the literature emphasizes that in recycled fiber-based nonwoven systems, the fiber blend ratio directly influences pore distribution and, consequently, airflow behavior [15].

### 3.4. Water Vapor Resistance Results

The water vapor resistance of nonwoven fabric samples is given in **Figure 7**. According to the results, water vapor resistance (Ret) decreases as the proportion of raising waste increases, indicating an increase in water vapor permeability. This behavior is attributed to the greater capacity of viscose fibers to absorb and transmit moisture through diffusion, owing to their hydrophilic and cellulosic structure, compared with polyester fibers [16]. The P100 sample, which consists of 100% polyester fiber, shows the higher water vapor resistance value. One of the inherent properties of synthetic fibers is hydrophobicity, therefore, it is an expected result that the decrease in the water vapor resistance occurs as the viscose fiber content in the fiber composition increases. In addition, the literature reports that increased porosity in nonwoven structures reduces water vapor resistance and improves moisture transfer [17]. The sample containing 70% raising waste (P30R70) exhibited the lowest Ret value, reflecting the combined effect of high porosity and viscose content. However, in terms of overall performance, the 50/50 blend ratio provided a balanced structure, which maintained improved moisture transfer and relatively high mechanical strength.

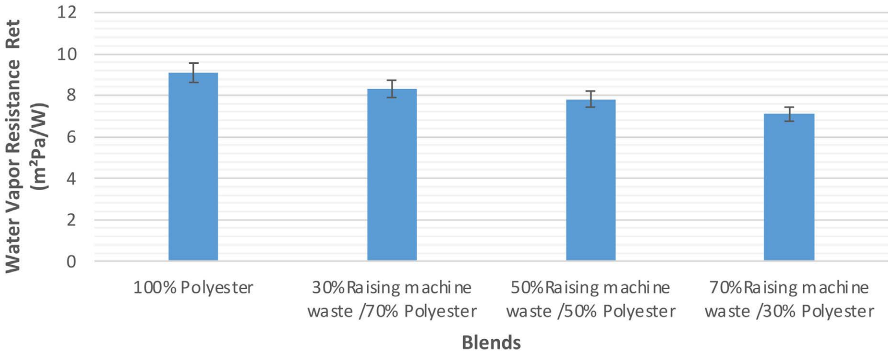


**Figure 7.** Water vapor resistance (Ret) values according to the blend ratios.

### 3.5. Thermal Resistance Results

The thermal resistance (Rct) results (**Figure 8**) show that the sample containing 100% polyester (P100) exhibited the highest Rct value, while Rct decreased as the proportion of raising waste increased. This behavior is attributed to the fact that thermal insulation in nonwoven structures largely depends on the amount of still air trapped between fibers, and a more compact fiber arrangement increases resistance to heat transfer [18].

As the proportion of raising waste increased, the structure became more open and permeable; the resulting increase in porosity facilitated convective heat transfer and consequently reduced thermal resistance. Similar trends have also been reported for recycled fiber-based nonwoven structures [19]. Within the scope of this study, the P50R50 blend ratio maintained an acceptable level of thermal resistance while providing advantages in air and moisture transfer, resulting in a more balanced thermophysiological performance.

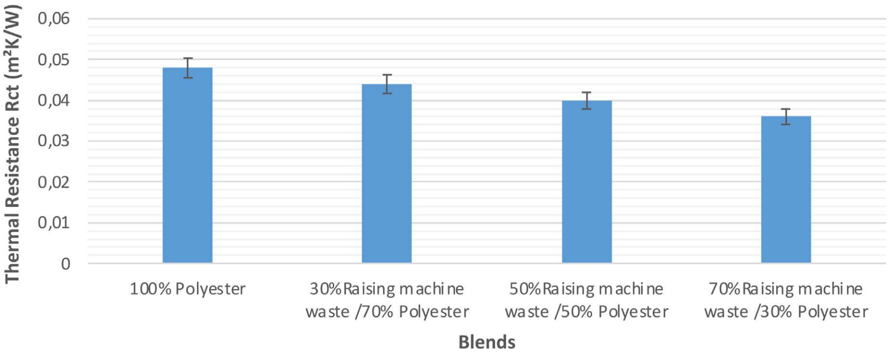


**Figure 8.** Thermal resistance rct values.

### 3.6. Fastness Results

The printing results were evaluated according to the fastness tests presented in **Table 4** below.

**Table 4.** Fastness results.

| Blends | Washing fastness | Dry rubbing | Wet rubbing | Light fastness |
|---|---|---|---|---|
| P100 | 4-5 | 4-5 | 4 | 5 |
| P70R30 | 4 | 4-5 | 4 | 5 |
| P50R50 | 4 | 4 | 3-4 | 4-5 |
| P30R70 | 3-4 | 4 | 3 | 4 |

The fastness results indicate that polyester-rich samples exhibited superior overall performance, particularly in light fastness and rubbing fastness. This behavior is attributed to the strong diffusion-based bonding mechanism of disperse dyes within the hydrophobic polyester matrix. As the raising waste ratio increased, a slight reduction in wet rubbing fastness and washing fastness was observed, likely because increased porosity and higher viscose content affected dye fixation stability. Similar trends have been reported for disperse-printed polyester and polyester-blend systems, in which dye–fiber affinity and structural compactness significantly influence fastness performance [20] [21]. Overall, the P50R50 blend demonstrated acceptable fastness values while maintaining balanced structural and comfort properties.

## 4. Conclusions

This study demonstrated that raising waste can be effectively utilized in the production of needle-punched nonwoven structures, offering a sustainable pathway for converting short and heterogeneous textile waste into value-added materials. The results indicated that both fiber composition and mass per unit area jointly influenced the mechanical and thermophysiological performance of the samples. Among the investigated blends, the P50R50 composition exhibited the most balanced performance, as it provided comparatively high tensile strength while maintaining moderate air permeability, improved moisture transfer (lower Ret), and acceptable thermal resistance without pronounced trade-offs. The observed improvements in air and moisture permeability with increasing raising waste content were mainly attributed to enhanced porosity and the presence of hydrophilic viscose fibers, whereas reductions in thermal resistance were associated with a more open structure facilitating heat transfer. However, it should be noted that variations in areal density also contributed to these trends, and therefore, the results cannot be attributed solely to fiber composition. The digital disperse printing application successfully added aesthetic and design value to the nonwoven surfaces. However, since functional performance tests were conducted on unprinted samples, the effect of printing on these properties was not evaluated within the scope of this study. The coral-inspired biomimetic approach established a conceptual correspondence with the porous structure of the material, offering a model for sustainable design and recycling-based production.

## Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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