

**ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL**

**IMPROVING THE COMFORT PROPERTIES OF SPACER FABRICS FOR  
SPORTSWEAR APPLICATIONS**



**M.Sc. THESIS**

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**Department of Textile Engineering**

**Innovative Technical Textiles Programme**



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**SPOR GİYİM UYGULAMALARINDA SPACER KUMAŞLARIN KONFOR  
ÖZELLİKLERİNİN GELİŞTİRİLMESİ**

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*To my family,*



## **FOREWORD**

To begin, I would like to express my sincere appreciation to Prof. Dr. Fatma Banu NERGİS for all helps and great guidances. I would like to thank to Prof. Dr. Cevza CANDAN for al helps about knitting and testing for this study.

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December 2022

Ayşe Berna KARABULUT  
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## **ABBREVIATIONS**

<b>FDY</b>	: Fully drawn yarn
<b>PA</b>	: Polyamide
<b>WVP</b>	: Water Vapour Permeability





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# **IMPROVING THE COMFORT PROPERTIES OF SPACER FABRICS FOR SPORTSWEAR APPLICATIONS**

## **SUMMARY**

Sportswear is the clothing including footwear, worn during sports or physical exercise and has an increasing demand due to lifestyle changes, increasing both sports organizations and health consciousness of people. The global sports apparel market is estimated to witness a Compound Annual Growth Rate (CAGR) of greater than 7% during the forecast period of 2022 to 2027. Bearing that into mind, it is no surprise to observe that the sports apparel with improved comfort properties have become more popular than ever. As is well known, comfort perception has four different aspects, such as thermo physiological, psychological, sensorial and wear comfort. In general, optimum thermal and moisture regulation, good air and water vapor permeability, rapid moisture absorption wicking and drying property, soft and pleasant touch are the most common characteristics sought in sportswear for satisfactory comfort properties. Enhancing the wearer's comfort is possible by engineering fabric structures by incorporating suitable fibers. For doing so, in this study, bilayered spacer fabric samples were produced with two different materials, on a Mayer & Cie Relanit 28 fine circular interlock knitting machine (30 inches in diameter and 92 feeders). 78/60x1 dtex S and Z twisted Recycle PA66 textured yarn (P) and 78/72 dtex S and Z twisted PA6-Umorfil textured yarn (U) together with 44 dtex Elastane were used for knitting both or one of the sides of the spacer samples. 22/1 dtex PA6 FDY monofilament yarn was employed as the spacer yarn. The samples were tested both in greige and dyed state and were conditioned under the standard atmosphere conditions (20 °C ±2, 65 % ±5%) before testing. Yarn and fabric tests, such as thickness, air permeability, stiffness, contact angle, water vapor permeability, wicking, drying rate, were conducted in accordance with the relevant standards.

The results of both greige and dyed PUD samples show that the moisture properties of PP double-sided Recycled-PA66 fabric are improved by making one side Umorfil which has more hydrophilic structure than Recycled-PA66. Comfort properties of fibers can be used in different parts of the garments depending on the intended use and purposes. Making the inner side of fabric as rcy-PA66 and the outer side of fabric as Umorfil gives cost saving production with improved comfort properties. The results indicated that use of Umorfil and Recycled-PA fibers in the fabric structure is not only suitable for active sportswear comfort but also is respectful to the environment.



## SPOR GİYİM UYGULAMALARINDA SPACER KUMAŞLARIN KONFOR ÖZELLİKLERİNİN GELİŞTİRİLMESİ

### ÖZET

Tekstil sektörü tüketimin en fazla olduğu sektörlerden biri olduğu için sektördeki geri dönüşüm yetersiz kalmaktadır. Bununla birlikte, çevre sorunları konusunda küresel farkındalığın artmasıyla birlikte artan sürdürülebilirlik çalışmaları, hem geri dönüştürülebilir ipliklerin hem de daha sürdürülebilir, çevre dostu liflerin bulunması ve farklı alanlarda kullanılmak üzere kullanım özelliklerinin geliştirilmesidir.

Spor giyim sektörü genel olarak sentetik lif içerikli ürünleri içermektedir. Spora olan ilginin artmasıyla birlikte spor giyim sektörü de hızla büyümekte ve bu ürünlerin yarattığı atıklar da artmaktadır.

Ayrıca insanların spor aktivitelerine yönelimleri arttıkça, spor giyimde koruyucu olarak kullanılan giysilerin konfor özelliklerinin iyileştirilmesi adına yapılan çalışmalar artmaktadır. Gelişen iplik ve makine teknolojisi sayesinde hem atkılı hem de çözümlü örme makinelerinde, hareket kısıtlaması olmaksızın, nem özelliği iyileştirilmiş teknik kumaşlar üretilmekte ve vücutta rahatlık hissi sağlanmaktadır.

Sandviç örgü yapıları, ileri makine teknolojisi ile üretilen ve geleneksel tekstil yapılarının karşılayamayacağı özellikler kazandıran özel yapılarıdır. Sandviç kumaşlar, esnek bir ürün yelpazesine ve üç boyutlu yapıya sahip olup, farklı malzemelerin aynı imalat sürecinde kullanılmasına imkan vermektedir. Otomotiv tekstiller, medikal tekstiller, jeotekstiller, spor giyim, iç ve dış giyim, koruyucu tekstiller ve kompozitler gibi birçok alanda kullanılabilir. Sandviç tekstiller teknoloji açısından çok yeni olmasa da özel tekstil yapılarına olan talebin artması ve bu özel tekstil yapılarının kullanım alanlarının geniş olması sayesinde sandviç tekstillere olan ilgi her geçen gün artmaktadır.

Bu tezde, nem yönetimi özellikleri üzerindeki etkilerini tayin etmek üzere iki farklı elyaf sandviç örgü yapısında kullanılmıştır. Bunlardan biri spor giyimde yaygın kullanılan ikinci elyaf tipi olan geri dönüşüm naylon, diğeri ise sürdürülebilirliğe katkı sağlamak üzere geliştirilmiş olan, yeni jenerasyon liflerden birisi olan rejenere Umorefil lifidir. Umorefil'den mamul ürünlerin konfor üzerinde etkisi olan nem yönetimi özelliklerinin, naylon, pamuk ve polyesterden mamul olanlara göre daha iyi performans sergilediği gözlemlenmektedir.

Bu tez kapsamında gerçekleştirilen ön çalışmalarda 44 numara yuvarlak örgü makinesinde 50 dtex PA6 Umorefil, 50 dtex Recycle-PA66, 44 dtex elastane, 20/1 monofilament ipliği kullanılarak kumaşların üretilmesi denenmiş ancak iğnelerin çoğunun kırılması nedeniyle üretim devam edememiştir. Daha sonra elastan kullanılmaksızın kumaşların üretilmesi çalışmaları yapılmış ancak iğnelerin zorlanması nedeniyle ticari üretim koşullarında elastan kullanılmaksızın çalışmanın mümkün olamayacağı görülmüştür. Ön çalışmalarda edinilen tecrübeler ışığında; iki katmanlı sandviç yapılı örme kumaşların üretimi Mayer & Cie Relanit 28 ince

dairesel interlok örgü makinesinde (30 inç çapında ve 92 besleyici) gerçekleştirilmiştir.

78/60x1 dtex Recycle-A66 (P) ile 78/72x1 dtex PA6-Umorfil (U) tekstüre iplikler sandviç kumaşların birer yüzünü veya her iki yüzünü örmek üzere, 22/1 dtex PA6 FDY monofilament iplik ve 44 dtex elastan ise ara iplik olarak kullanılmıştır. Ara iplik olarak kullanılan 22/1 dtex PA6 monofilament ipliği ilmek yapmamakta ve sadece her iki kumaş yüzeyi örülürken ortasında örgü yapmadan yüzecek şekilde yapıya yerleşmektedir. Böylelikle her iki yüzü de P, her iki yüzü de U ve bir yüzü P, diğer yüzü U ipliklerinden örülecek şekilde üç çeşit kumaş geliştirilmiş olup, bu kumaşlar hem ham (G), hem de boyalı (D) olarak test edilmişlerdir.

Uygulanan tüm testler öncesinde numuneler standart atmosfer koşullarında (20 OC  $\pm$ 2, %65  $\pm$ %5) şartlandırılmıştır. İpliklerin numaraları tayini için ISO 2060, kopma kuvveti ve uzaması tayini için ISO 2062 standardı kullanılmıştır. Kalınlık ölçümü ISO 5084 standardına göre 20 g/cm<sup>2</sup> basınç altında R&B Kumaş Kalınlık Test Cihazı'nda yapılmıştır. Hava geçirgenliği testi, ISO 9237 standardına göre 200 Pa basınçta 20 cm<sup>2</sup>'lik test yüzey alanında yapılmıştır. Su buharı geçirgenlik testleri ve kumaş sertliği tayini için sırasıyla BS 7209:1990 ve ASTM D 4032 standardı kullanılmıştır. Tüm numunelerin temas açısı, Cam 101 temas açısı gonyometresi (KSV INSTRUMENTS) kullanılarak ölçüldü. Kılcal ıslanma testleri için eni 25 mm x boyu 200 mm şeklinde dikdörtgen olarak kesilerek hazırlanan numuneler numuneler 5 mm distile suyun içerisinde kalacak şekilde düzenek hazırlanmıştır ve her 5 dakika distile suyun kumaşta yükselişi izlenerek not edilmiştir. Kuruma hızları için numuneler 30 dk 1 lt distile suda ıslatıldıktan sonra kurumaya bırakılmış, her saat ağırlıkları ölçülmüş ve 105% ağırlığına geldiklerinde test sonlandırılmıştır.

İplik test sonuçları dikkate alındığında aynı iplik numarasına sahip olan hem Recycle-PA66 hem de Umorfil-PA6 ipliklerinin mukavemet ve uzama sonuçları birbirine yakın çıkmıştır. Bu nedenle Umorfil-PA6 ve Recycle-PA66 iplikleri aynı pozisyonda, birbirlerinin muadili olarak değerlendirilebilmiş ve aynı makine ayarı kullanılarak bir yüz Umorfil bir yüz Recycle-PA66 olacak şekilde çift yüzlü kumaş örülebilmıştır.

Kumaşların fiziksel test sonuçlarına bakıldığında;

Ham numunelerin kalınlık, gözeneklilik ve kumaş yoğunluğu değerlerinin, boyalı numunelerin bu değerlerinden daha yüksek olduğu görülmüştür.

Kumaşların sertlik sonuçları, UPG ve PPG numunelerinin daha yüksek sertlik sonuçlarına sahip olduğunu, UPD ve PPD numunelerinin en düşük sertlik sonuçlarına sahip olduğunu gösterdi. Daha düşük kalınlığa sahip boyalı numuneler daha düşük sertlik değerlerine sahipti. Daha yüksek ağırlığa sahip daha hacimli yapılar daha yüksek sertliğe sahiptir. Düşük rijitlik, boyarmadde ve boyama kimyasal etkisinden kaynaklanabilir.

PPD kumaşı, en yavaş ve en düşük kılcal ıslanma yüksekliği sonuçlarını gösterdi. Umorfil kullanılan UUD ve UUG kumaş numuneleri en yüksek ve en hızlı fitilleme sonuçlarını göstermiştir. PUD ve UPD kumaşlarının sonuçları göstermiştir ki Recycle-PA66 numunelerinin fitil özelliği kumaşın tek yüzüne Umorfil kullanılmasıyla artırılmıştır.

Kuruma hızları karşılaştırıldığında, daha yüksek ıslanma yüzdesine ve fitilleme yüksekliğine rağmen, ham kumaş numunesinin kuruma hızı daha hızlıdır; bunun nedeni, boyanmış numunelerin daha yüksek yığın yoğunluğu ve daha düşük gözenekliliği olabilir.

Umorfil kumaş örneklerinin su emiciliği, su buharı geçirgenliği ve hava geçirgenliği daha yüksek olmuş, ancak Recycle-PA66 düşük su emiciliği nedeniyle daha hızlı kurumuştur. Giysi hızlı kuruma amacına ihtiyaç duyduğunda, Recycle-PA66 önerilir.

Önemli olan havanın emilmesi, yüksek hava ve su buharı geçirgenliği ve iyi emicilik olduğu durumlarda Umorfil önerilir. Böylece elyafların rahatlık özellikleri kullanım ve amaçlara bağlı olarak giysilerin farklı kısımlarında kullanılabilir. Hava geçirgenliği, kuruma hızı, su buharı geçirgenliği, temas açısı ve fitilleme testleri gibi test edilen özelliklerin sonuçları, bu elyafların spor giyim eşyası üretiminde kullanılabilirliğini göstermektedir. Umorfil yüzeyinden uygulanan rijitlik testi, boyalı numunede daha düşük, Umorfil tabakasında daha yüksek değerler elde edildiğinden, bir boşluk yapısının dış yüzeyinde Umorfil kullanılması önerilebilir.

Maliyetlendirme sonuçları, Recycle-PA66 ipliklerinin fiyatının umorfil ipliklerinden daha ucuz olması nedeniyle, Recycle-PA66'lı kumaşların tüm numunelerden daha ucuz olduğunu göstermiştir. PUD ve UPD kumaşlar kullanılarak nem konfor özelliği ile maliyet tasarrufu sağlanacaktır.

Bundan sonraki çalışmalarda spacer kumaşların farklı yüzlerinde farklı ipliklerin denenmesi veya katlar arası boşlukların açılması ve bunun konfor özelliklerine etkisinin incelenmesi önerilmektedir.



## 1. INTRODUCTION

Textile industry is one of the sectors that result in the highest raw material consumption and, with the increase of global awareness on environmental problems, sustainability studies which focus on the use of recyclable yarns for fabric production and the development of sustainable, eco-friendly fibers are growing.

The sportswear sector generally includes products made of man-made fibers. With the increasing interest in sports, the sportswear industry is growing rapidly, and the leftovers created by these products are also increasing.

Moreover, the improvement of the comfort properties of the clothing used as a protector in sportswear increases the sports efficiency.

Thanks to the developing yarn and machine technology, both weft and warp knitting machines enable the production of technical fabrics with improved moisture properties and to ensure comfortable feeling to the body without restricting movement and unhealthy inner conditions.

Sandwich knit structures are special textile structures produced with advanced machine technology and give features that cannot be met by conventional textile structures. Sandwich fabrics have a flexible product range and three-dimensional structure and allow the use of different materials in the same fabrication process. It can be used in many areas such as automotive textiles, medical textiles, geotextiles, sportswear, underwear and outerwear, protective textiles and composites. Although sandwich textiles are not very new in terms of technology, the interest in sandwich textiles is increasing day by day thanks to the increase in demand for special textile structures and the wide range of use of these special textile structures.

In this thesis, two sustainable fibers are used for producing spacer structure with good moisture management properties. One of the fibers is Recycled-PA66 nylon, which is the second widely used fiber in sportswear, and the other one is Umorfil, which is a new generation regenerated fiber that contributes to sustainability.



## **2. LITERATURE REVIEW**

### **2.1 Sportswear**

Textiles were classified into two parts; conventional textiles and technical textiles by the Textile Institute (McIntyre & Daniels, 1995). Conventional textiles are used for common applications and decorative or aesthetic purposes. Technical textiles, in other words, Hi-Tech Textiles are the term to explain technical and high-performance, high-added-value products for particular end-use rather than conventional. These textiles are produced to meet predefined performances or functionalities (McCarthy, 2016; McIntyre & Daniels, 1995; Rasheed, 2020).

The main functions of conventional textiles are basically to protect the user's body from the surroundings, to show wealth and status, and to meet the physical and psychological needs of users.

On the other hand, functional textiles have a wide range of properties in their specific technical fields and some of their main functions are high flexibility, resistance to chemicals, biologicals or mechanical forces, possibility of using as reinforcement, filtration, conductivity, insulation, etc. purposes (McCarthy, 2016). Technical textiles can have one of these high functions or can be multifunctional by combining these.

High-performance apparel, one of the technical product groups of high-function textiles, is developed with special engineering techniques to meet certain high performances and functions, rather than conventional clothing (McCarthy, 2016).

Sports textiles are a sub-branch of technical textiles (Paul, 2019) and also one of the high-performance apparel used to protect the human body during sports. Sports clothing, particularly the base layer garments which are next to the skin, are important for providing the thermo-physiological comfort of a person and for keeping their performance high (Kumar, 2020; Rasheed, 2020).

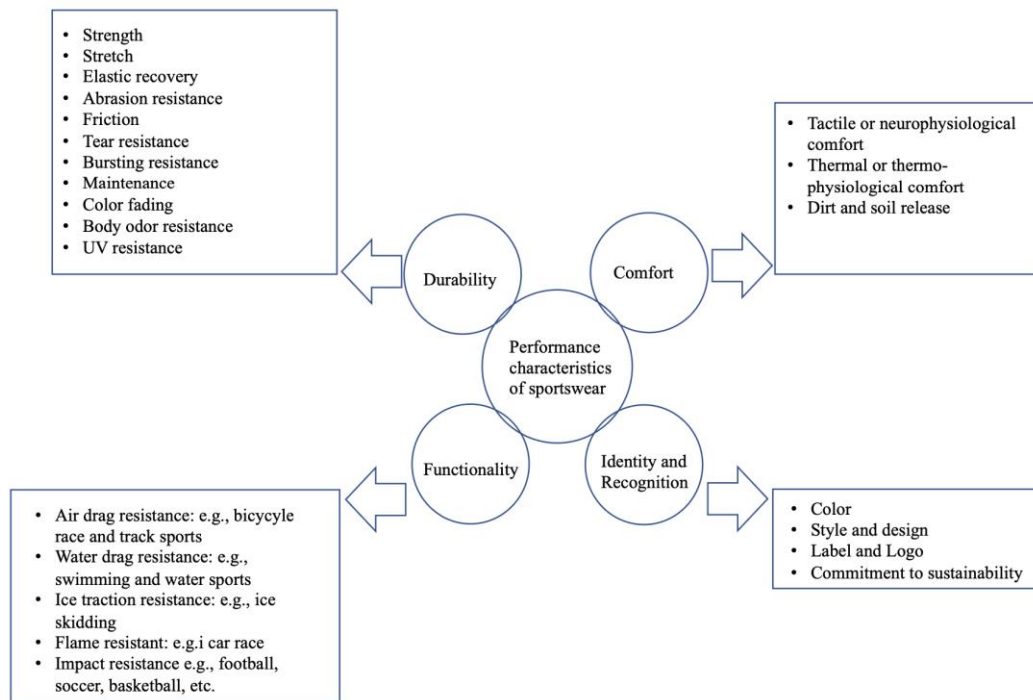
In all kinds of sports, which mainly are winter sports, summer sports, outdoor games, indoor games, football, cricket, climbing, cycling, flying and sailing sports, athletics, etc, several textile materials are used having different functionalities (Uttam, 2013).

All garments worn during sports can be listed in sportswear, such as shorts, tracksuits, t-shirts, polo shirts, wetsuits, jockstrap, etc (Paul, 2019).

As people's working schedules and working hours change, they start to devote more time to themselves, and at the same time, the awareness of sports for health increases among humanity, the interest in sports has increased and more expectations have arisen on sportswear in line with these needs. Many studies and technologies have been developed to meet functional expectations in sportswear (Lai et al., 2022; Uttam, 2013).

Users' main problems when using sportswear are considered as sweating, feeling hot during exercise, low stretching ability, extra weight of the fabric, injuries during falling, excessive movements, hard contact with the ground (Jhanji, 2021; Paul, 2019; Uttam, 2013). Major performance requirements for sportswear are both listed as follows and are shown in Figure 2.1:

- High comfortability, easy to wear, good handling,
- Good thermal properties; cool in summer, warm in winter,
- Lightweight, high elasticity, good compressivity, independence movement,
- Good moisture management, remove and distribute the moisture from the body and quick dry,
- High perspiration fastness, high strength and durability, good abrasion resistance,
- Easy-care
- Good skin-care; protect skin from UVA, UVB, anti-bacterial, and gentle feeling to skin.



**Figure 2.1 :** Performance characteristics of sportswear(Elmogahzy, 2020).

Since it is difficult to meet all these features with a single fiber in a single product, combining different fibers for different functions, multilayer fabrics, coatings, finishes, composites etc. are generally used in sportswear.

Sports apparel market has huge size on the whole Textile markets. The global sports apparel market is estimated to witness a Compound Annual Growth Rate (CAGR) of greater than 7% during the forecast period of 2022 to 2027 and it was estimated to generate around 191 billion U.S. dollars in revenue in 2022 (Smith, 2022). Rising revenues are forecast to continue and reach around 249 billion U.S. dollars in 2026. And the forecast report includes that the main properties of sportswear products are the product's capability to offer sweat-wicking & breathability and enhancement of physical movement, improves blood circulation, injury preventions. Some of the key market players are Adidas, Columbia, FILA, New Balance, Nike, Lululemon Athletica, PUMA, Ralph Lauren, Under Armour etc (Smith, 2022).

### **2.1.1 Fabric structures and systems in sportswear**

It is not enough to provide so many features expected from sportswear with a simple structure of a single fiber. For this reason, the right fibers have been used in different parts of sports products with various textile structures and studies have been carried

out on which fiber will exhibit better properties in which fabric, these studies are still continuing.

The basic properties of the fabric structure to be used in sports products can be examined by the fiber type, the weave structure, the weight, the thickness of the material and finishing processes (Uttam, 2013).

Both natural and synthetic fibers are used in sportswear.

One of the most common fibers used in textile is cotton which can absorb high levels of moisture, but low wicking properties make cotton to dry slowly when wet and stick to the skin. This slow drying problem can cause rapid and undesirable heat loss when the activity is stopped, as well as an increase in the weight of the garment, which can impair athletic performance (Sathish Babu et al., 2020).

Moreover, there are some special fibers such as sportswool that are produced with special properties for sportswear. Sportswool was developed to improve moisture properties by The Woolmark Company in 1994. It has a hybrid structure that is composed of a fine Merino wool sub-layer for insulation and a polyester exterior which draws moisture away from the wool layer to the surface. Sportswool absorb the sweat vapors then disperse to the air to avoid heat increasing on the body and/or wetness(Chaudhari et al., n.d.).

One of the reasons why synthetic fibers are preferred is that they are moisture repellent and do not become heavy (Sathish Babu et al., 2020).

Widely used in activewear and sportswear, polyester has a lower absorption capacity and higher wicking rate than cotton. Polyester has exceptional dimensional stability and offers excellent resistance to dirt, alkalis, rot, mold and most common organic solvents. Durable yet lightweight, elastic and comfortable, smooth-feeling, all of these are consumer-important attributes for a wide variety of sportswear applications. Its excellent heat resistance, good moisture transport properties, low moisture absorption, easy maintenance properties and low cost make it very useful for sportswear (Uttam, 2013).

Nylon has higher moisture absorption than polyester. Despite its very low moisture absorbency, polypropylene has high moisture vapor permeability and wicking properties and can remove sweat from the skin without absorbing it.

Acrylic fibers are used in the form of high pile fleece fabrics in activewear and sportswear with low moisture absorption (Sathish Babu et al., 2020).

In general, sportswear fabrics are made as single-layer knitted fabrics. Single-layer knitted fabrics made of cotton are considered comfortable when used under normal conditions. Single-layer polyester, nylon, polypropylene and acrylic knitted fabrics are suitable for strenuous activities as they have a higher wicking rate than cotton.

Single jersey knit structures are widely preferred as the base layer for sportswear fabrics. The single jersey fabrics have better softness, which provides more comfort, less tactile sensations with skin fit garments. It also has good extensibility and recovery, freedom of movement, shape retention, and tailored fit (ÖZDİL & ANAND, 2014). Single jersey fabric structural form has higher transfer wicking ratio and lower liquid moisture contact angle than tight fabric structural form (Kumar, 2020).

Various fiber combinations give sportswear fabrics better functional properties and the highest performance characteristics than a single fiber type.

The invention of highly elastic fibers was probably the most important step in the evolution of sportswear. In the development stages, there were small parts of products including elastane, such as lycra, in their structure, but now whole garments are made of elasticated materials. They are also important in injury treatments like compression bandages.

Also, the use of superfine or microfiber yarn enables the production of dense fabrics that lead to more effective capillary action with better thermo-physiological regulation.

A wide variety of woven, knit and nonwoven fabrics are commercially available for sportswear and casual wear. These fabrics vary in terms of entrapped air, pore shape and size, volume and surface properties, etc.

In sportswear, knitted fabrics are preferred because they have more elasticity and stretching properties compared to woven fabrics, providing unlimited freedom of movement and the transmission of body steam to the next textile layer in the clothing system.

Layered fabrics for active sportswear have become common because they can combine multiple features. The performance of the layered fabric in thermophysiological regulation is better than the single-layer textile structure. Each layer has a separate function; The layer next to the skin is to quickly expel the sweat to the outer layer, which absorbs and evaporates and disperses it to the atmosphere. In doing so, it takes some of the body heat and keeps the body cool. A synthetic material with good moisture transfer properties, such as polyester, nylon, acrylic or polypropylene, can be preferred to be used in the inner layer of the fabric while a material having good moisture absorption e.g., cotton, wool, viscose rayon or their blends, can be placed to the outer layer. The conductive inner layer rapidly transfers liquid sweat to the absorbent outer layer, mainly as a result of capillary action (Uttam, 2013).

Various finishing agents such as water-repellent finish, wicking-enhancing finish, hydrophilic finish, and newer nano-finishes are applied to alter the transmission properties of fabrics.

### **2.1.2 Studies on moisture management in sportswear**

The term comfort is defined as “the absence of unpleasantness or discomfort” or “a neutral state compared to the more active state of pleasure” (Milenković et al., 1999). As is well known, comfort perception has four different aspects, such as thermo physiological, psychological, sensorial and wear comfort.

Psychological comfort is mainly related to the latest fashion trend and its acceptability in society and has little to do with the properties of fabrics. Tactile/comfort is related to the fabric surface and mechanical properties. Thermal comfort relates to the fabric's ability to maintain the temperature of the skin through the transfer of heat and sweat generated in the human body (Das & Ishtiaque, 2004).

In general, optimum thermal and moisture regulation, good air and water vapor permeability, rapid moisture absorption wicking and drying property, soft and pleasant touch are the most common characteristics sought in sportswear for satisfactory comfort properties. Enhancing the wearer's comfort is possible by engineering fabric structures by incorporating suitable fibers.

Thermophysiological comfort is affected by the breathability and moisture management properties of the fabric. Clothing acts as a barrier for heat and vapor

transfer between the skin and the environment. Moisture transmission across the fabric occurs in three ways, such as moisture diffusion across the fabric due to moisture vapor gradient, moisture absorption-desorption by hydrophilic regions on the fabric, and moisture transmission via convection mode through moving air close to the skin. The moisture absorbency and transmission rate of the fabric have a significant effect on the moisture of the skin. Because of the increased metabolism during sports, there is an increase in the body temperature and the body carries it out through sweating in order to keep body core temperature at 37 degrees. This heat and energy thrown out of the body must be expelled in order to maintain body comfort, and one of the primary tasks of sportswear is to expel this excess energy, sweat and heat (Das & Ishtiaque, 2004; Kumar, 2020; Pamuk, 2008).

The main purpose is avoiding the feeling of wet and hot, avoiding sweat and burning of skin. In general, the faster a fabric can wick moisture, the more surface area the moisture covers, in turn allowing the evaporation of the moisture to occur faster leaving the wearer dry and comfortable. Bearing that into mind, it is no surprise to observe that the sports apparel with improved comfort properties have become more popular than ever.

Depending on the type of the sports activity, the human body is expected to produce between half and one liter of sweat per hour. Base layer fabrics must absorb and simultaneously disperse heat and moisture to achieve a high level of comfort (Senthilkumar et al., 2012)

In their study, Choudhary and Ramratan (2020) evaluated the effect of fiber content and fabric structure on moisture management through supporting factors such as fabric thickness, porosity, and contact angle. The overall results show that moisture management properties are directly proportional to porosity, meaning that plain jersey fabric, which has the most porous structure, shows the best results of moisture management among the three fabric structures. Also, the micro-polyester is better than the other two because of the more capillary channels available to quickly move the liquid from the top surface to the bottom surface. On-the-go, fabric with good porosity, i.e. with less areal density or quick moisture transport capacity using micro-polyester single jersey, is envisioned to prove to be competent among other alternatives.

Suganthi and Senthilkumar (2018), investigated the moisture management properties of double-layered knitted structures with different yarn combinations from viscose, modal, bamboo, polypropylene, micro-fiber polyester and polyester fibers in the inner layer and outer layer and evaluated the effects of yarn count, fabric thickness, areal density changes on the absorbency ability of the samples. It was observed that the drying rate was affected by thickness and areal density. It is stated that double-layer knitted fabrics can be preferred in sportswear because they have good moisture management, as they quickly release sweat from the skin to keep the wearer dry.

Çeven and Günaydın (2021) searched comfort and mechanical properties of different regenerated cellulosic fibres, different yarn types and process. It was observed that negative correlation between the fabric samples' fabric weight and the air permeability values and air permeability was attributed to porosity of fabrics, and Umorfil yarn provided the maximum air permeability.

Khan and friends (2018) observed that plated jersey and hybrid plaited jersey structures from cotton, polyester, rayon fibers had better moisture management properties compared to single jersey knitted structures.

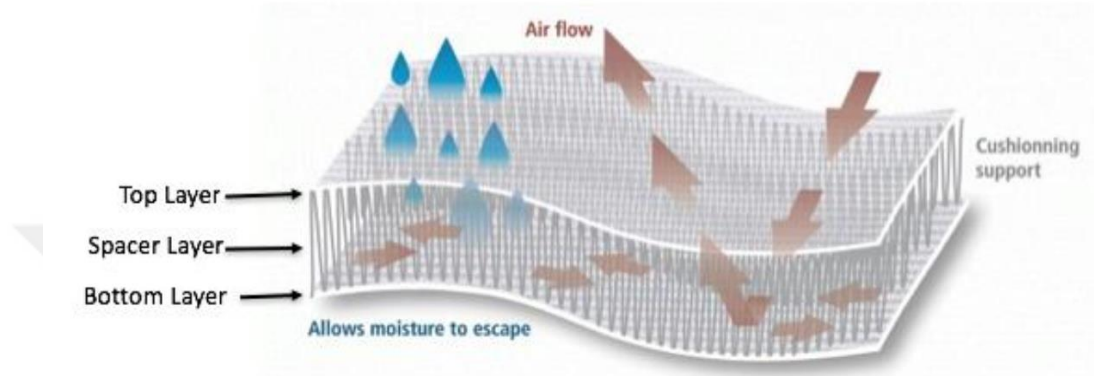
Suganthi and friends (2023) studied on moisture management behavior of the natural and manmade cellulosic fabrics from cotton, bamboo, modal, tencel and the results showed that shortest wicking time with longest radius of wicking gives high spreading speed and superior moisture management which was modal fibers in the study.

Buhai and friends (2014) studied on comfort properties of multilayer weft knitted spacer fabrics by porosity and thickness. It was observed that thickness has a significant influence on water vapour permeability and thermal resistance.

Chen and friend (2016) worked for high porosity, good comfort, good thermal properties, moisture absorption and softness with changing physical knitting structure of spacer yarn from polyester fibers. The results showed that porosity, thickness and area density were related with linear density of yarn and spacer yarns amount per unit. Also, they stated that for the wearing comfort requirements, the air and water-vapor permeability could be controlled by changing structure of spacer fabrics.

## 2.2 Spacer

Spacer fabric is three-dimensional (3D) textile fabric with a multilayer sandwich shape. Spacer structure has a middle layer mostly with monofilament yarn and two outer layers as can be seen in the Figure 2.2 below. These two outer layers can be formed of knitted fabric or woven fabric and the middle with filaments layer keeps the two outer layers together (Pablo et al., n.d.).



**Figure 2.2 :** Breathability and moisture transfer of spacer fabric structure(Doran, 2016).

Spacer fabric gives the opportunity to combine different yarn and fabric properties. The middle part of the spacer makes the structure highly breathable and has good moisture properties with higher comfort rather than foam, neoprene and laminate fabrics (Pablo et al., n.d.). This makes the spacer fabrics eco-friendly textile materials which are recyclable.

Machine adjustments give opportunity to change thickness, pore size and fabric structures to meet consumer requests according to final usage. Different fibers can be used in the inner and outer surface, mono or multifilaments in the middle of layers. These changeable structures give different pore size, different properties of fibers, different thickness, stiffness, and air and water permeabilities, etc. All these advantages make spacer fabrics more preferable than conventional textiles.

It can be used in many areas such as automotive textiles, medical textiles, geotextiles, sportswear, underwear and outerwear, protective textiles and composites (Pablo et al., n.d.). With the developing technologies and increasing demands in the textile world, spacer fabric uses and studies are increasing.

There are three spacer production categories; woven spacer fabrics, warp-knitting, weft-knitting, flat knitting and circular knitting spacer fabrics. In these fabrics, the spacer filaments are composed of monofilament or multifilament (Pablo et al., n.d.).

### **2.2.1 Spacer fabric production**

Based on the structure of the outer layer fabric, there are three spacer production categories; warp-knitted spacer fabric, weft-knitted spacer fabric and woven spacer fabric. In these fabrics, the spacer filaments are composed of monofilament or multifilament (Pablo et al., n.d.).

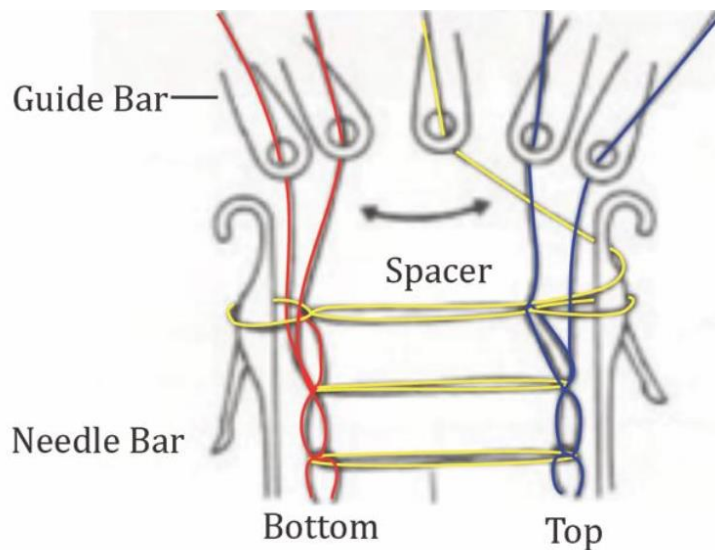
Woven spacer fabrics are textile surfaces produced as double-layered structures from two different woven fabrics. One of the production of woven spacer fabrics is carried out on pile fabric weaving machines. In these machines, the two outer textile surfaces produced in sandwich form are combined with pile spacer threads. Another production method of woven spacer fabrics is that the spacer woven fabrics are constructed of woven outer layers and woven crosslinks instead of pile yarns (Mountasir et al., 2011).

The structure can be elastic or rigid, thickness of spacer can be between 10 mm and 100 mm and also the space of structure can be filled with functional components.

Woven sandwich textiles are used in automobile interior components, soundproofing materials, surgical implants, the air and space industry, wall elements, floor panels, inner coverings, and insulation as components, etc.

#### **2.2.1.1 Warp knitting spacer**

Spacer fabrics can be produced in warp knitting machines in a double-sided structure and by connecting with the spacer yarn of each face as the location of spacer yarn can be seen in the Figure 2.3. Monofilament yarns are generally chosen as the connecting yarn. Both faces can be the same as well as different patterns and/or different thicknesses. Warp knitting machines give the separate production option for two sides, different yarns and different patterns can be used on both needle bed. The thickness of spacer fabric is determined by the distance between the needle plates. The thickness of the spacer varies between 1.5 mm and 60 mm, depending on the design of the machine (Bruer et al., 2005; Fuchs et al., 2003).



**Figure 2.3 :** Spacer yarn location between face and back loops on warp knit machine (Spencer, 1989) (Spencer, 2001, p. 368).

Main studies of warp knit spacer fabrics were about polyester yarn about thermal comfort properties.

Chen and friends (2021) worked thermo-physiological properties of warp knitted polyester spacer fabric in terms of water vapor permeability, air permeability, vapor permeability, thermal and heat permeability and the results showed that the water vapor permeability of fabrics increased when thickness decreased and volume density increased. Another results was that the higher volume density samples with similar thickness gived in lower water vapor permeability and higher water absorption due to more air contained in spacer fabric and proper pore size.

The another study of Chen and friends (2022) was about warp knitting spacer with different knitting structures and polypropylene and polyester yarns. The research was mainly on structural properties of spacer fabric and one of the results was that the density of the fabric increases, the structure of the fabric becomes more compact, the volume density increases, and the channels for air pass through become less and density, thread type, and yarn type also affected moisture management property. Also yarn and part thread could highly enhance air permeability.

### **2.2.1.2 Weft knitting spacer**

Another spacer knitting production type is weft knitting and can be produced by using spacer in circular knitting machines with additional yarn feeder in double needle bed and flat knitting machines with V bed (Bruer et al., 2005).

Conventional knitting machines for the production of sandwich textiles have been modified with additional equipment and different machine adjustment possibilities. The thickness of spacer fabric can be determined with upper needle bed height.

#### **Flat weft knitting**

In flatbed knitting machines, spacer fabric is produced by cross-linking the yarns of two surfaces. Different yarns and patterns can be used for both surfaces. The height of the spacer layer depends on the distance at which the needle beds can be moved apart in these machines. The thickness of spacer can be in flat bed knitting machines varies between 2-10 mm (Bruer et al., 2005).

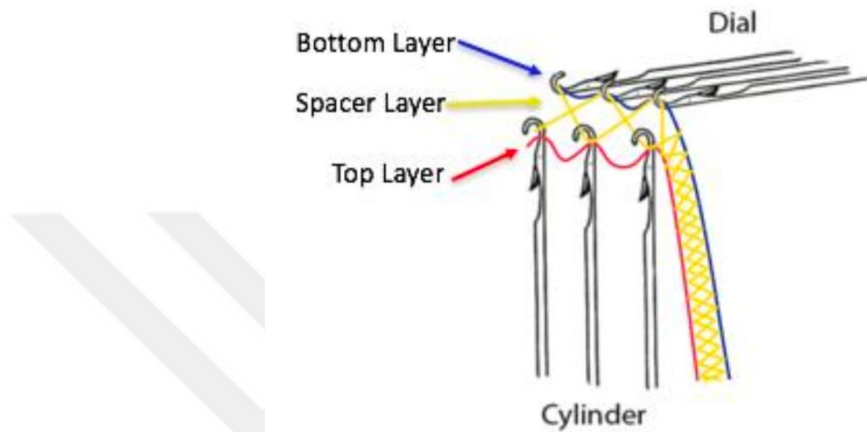
#### **Circular weft knitting**

In circular knitting machines, spacer knitting is done by feeding different yarns to the dial and cylinder needles, and generally by making a connection between the cylinder and the dial with monofilament yarn (Bruer et al., 2005; Ilgaz, 2007).

The thickness of spacer fabric depends on the height at which the upper needle bed can be lifted from the roller. The maximum thickness of spacer in circular knitting machines could be 15 mm (Ertekin, 2009).

In double-bed circular knitting machines, two separate layers of fabric, which are formed by feeding different yarns to the dial and cylinder needles, are usually interconnected with monofilament yarn which was illustrated in the Figure 2.4 (Doran, 2016). In circular knitting machines, yarn must be fed from at least 3 different systems for the production of spacer fabric. The two layers of fabric knitted by the cylinder and dial needles are joined by the tuck movements of the spacer yarn on the cylinder and the dial, and in this way, the spacer yarn are not clearly visible on both surfaces of the fabric.

The monofilament yarn as spacer is preferred as rigid yarn to get even thickness all over the fabric. Also, this monofilament yarn is kept two layer separate. This prevents the deformation of the fabric under load during use. Non-monofilament yarns are not preferred much because they do not provide the required rigidity. The disadvantage of monofilament threads is that they cause rapid wear of the surfaces in contact with the thread and shorten the needle life in the machines (Ertekin, 2009).



**Figure 2.4 :** Spacer knit structure on double jersey circular knit machine (Doran, 2016).

With the ease of different yarn feeds, circular knitting machines gave the opportunity to make different product combinations with two-sided different fibers in spacer fabrics.

Literature searches have shown that a lot of study has been done on warp knit spacer, and most studies have been on polyester, regenerated fibers and cotton, the list of some of the studies in Table 2.1. There are very few studies in the literature with Umorfil fiber. For this reason, spacer production in circular knitting machine using Umorfil fiber was preferred. To make the study more specific, two different fiber studies were conducted and the values were compared.

Table 2.1 : Table for previous studies.

Author	Spacer fabric type		Fiber Types		Parameters							
	Weft Knitted Spacer	Warp Knitted Spacer	Same fiber for Both Face	Different fibers for front and back	Porosity	Thickness	Air Permeability	Water Vapour Permeability	Drying Rate	Compression	Wicking	Thermal Properties
(Chen et al., 2021)		✓	✓			✓	✓	✓				✓
(Ertekin & Marmarali, 2011)	✓			✓			✓	✓				✓
(Blaga et al., n.d.)	✓			✓	✓	✓	✓	✓				✓
(Choudhary & Ramratan, 2020)	✓		✓		✓	✓	✓				✓	
(Muthu Kumar et al., 2022)		✓	✓		✓	✓	✓	✓		✓		✓
(Rajan et al., 2016)		✓	✓		✓	✓	✓	✓				✓
(Buhai et al., 2014)	✓			✓	✓	✓	✓	✓				✓
(Bagherzadeh et al., 2012a)		✓		✓	✓	✓	✓				✓	
(Arumugam et al., 2018)		✓	✓		✓	✓	✓	✓				✓
(Liang et al., 2021)		✓	✓						✓		✓	
<b>Current work</b>	✓			✓	✓	✓	✓	✓	✓		✓	

### 3. EXPERIMENTAL WORK

#### 3.1 Material

78/60x1 dtex, S and Z twisted, Recycled-PA66 textured yarn (P) and 78/72 dtex, S and Z twisted, PA6-Umorfil textured yarn (U) were used for knitting either both or one side of the spacer samples. In order to prevent the spirality problem, one S and one Z twisted yarn was placed onto the knitting machine creel consecutively. A 22/1 dtex PA6 FDY monofilament yarn was employed as the spacer yarn and a 44 dtex elastane is used while knitting front and back sides of the samples.

Umorfil is a new generation protein fiber obtained from a fish scale developed by Dr James Hou. The name Umorfil consists of the combination of the Latin "Umor" and the French "Fil" words, and "Umor" refers to moisture and "Fil" to yarn (*Umorfil Launches New Revolution in Nylon 6*, n.d.). Umorfil is a fiber that aims to help reduce the world's food waste and pollution problem by upcycling large amounts of fish scales. 1 kg of Umorfil N6U yarn was made from approximately 450 fish scales. General properties of bionic Umorfil fibers are being eco-friendly due to the collagen peptide structure, skin friendly. They cause no irritation, have good moisture regain, UV protection and, natural cool feeling.

Umorfil fibers have 3 different types as Umorfil® N6U®(Nylon), Umorfil® T®(Polyester), Umorfil® Beauty Fiber®(Viscose).

UMORFIL N6U, the type used for developing the bilayered samples of the study, gives better hand-feeling with deep dyeable features, higher moisture regain, natural cooling effect and anti-UV function, and skin friendliness. Some recent studies report that the moisture related properties of the products produced from Umorfil yarns, are better than those of Nylon, Cotton and Polyester ones (Çeven & Günaydın, 2021; Kırıcı et al., 2021).

Recycled-PA 66, which is the other type of fiber used for the study, was obtained from Fulgar with traceability certifications.

## **3.2 Sample Preparation**

### **3.2.1 Preliminary studies and fabric production**

At the beginning of the study, a 44 fine circular knitting machine was used to produce spacer samples from 50 dtex PA6 and Umorfil yarns and 44 dtex elastane without changing any production parameter. Under those working conditions most of the needles were broken and production could not proceed. The production trials continued without using elastane, however the machine also couldn't run under these conditions and most of the needles were almost broken.

In the light of the experience gained during preliminary studies, the yarn and knitting parameters for bilayered spacer fabric sample production were changed and established as follows:

78/60x1 dtex S and Z twisted Recycled-PA66 textured yarn (P) and 78/72 dtex S and Z twisted PA6-Umorfil textured yarn (U) were used for knitting both or one of the sides of the spacer samples.

22/1 dtex PA6 FDY monofilament yarn was employed as the spacer yarn. Spacer monofilaments were tucked on opposite front and back needles.

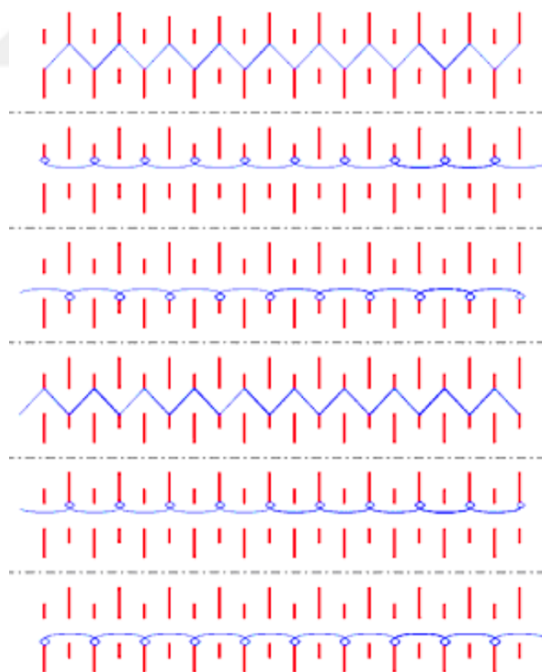
44 dtex elastane is fed with Umorfil and Recycled-PA66 yarns while knitting the front and back side of the fabrics.

The samples were produced on a Mayer & Cie Relanit 28 fine circular interlock knitting machine (30 inches in diameter and 92 feeders, Figure 3.1) in Aydın Öorme San Tic A.S. company. During the production, 90 systems are used, 30 systems were for front yarns, 30 feeding systems were for back yarns and. 30 systems were for the spacer yarn. Yarn knitting report was showned in Figure 3.2.



**Figure 3.1 :** Circular Knitting Machine.

Production speed was 18 revolution/min.



**Figure 3.2 :** Knitting report for spacer fabric (Ertekin, 2009).

### 3.3 Method

All tests, both for greige and dyed fabrics, were conducted after conditioning the samples under standard atmospheric conditions (20 0C ±2, 65 % ±5%).

The Recycled-PA66 textured yarn and the PA6-Umorfil textured yarn were either used on both of the spacer samples or only on one of the sides.

The samples were dyed and finished according to the following commercial procedure:

- Bianco washing at 80 degree with wetting agents.
- Prefixation in 10 chambers stenter machine at 90 degree for 45 sec.
- Dyed in Beam Dyeing Machine 102 degree Celsius for both Umorfil and Recycled-PA66 dyeing process.

Coding of the samples are given in Table 3.1 where;

P is for the recycled PA66 textured yarn,

U is for the PA6-Umorfil textured yarn,

G is for the greige state of the fabric,

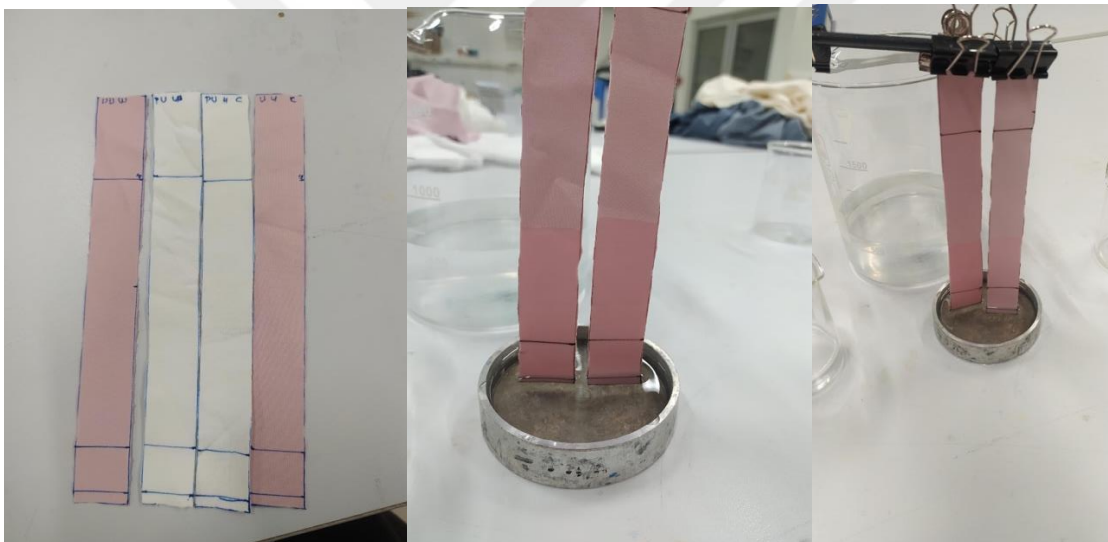
D is for the dyed fabrics.

**Table 3.1** : Coding of the samples.

Fiber Content	Greige Fabric	Dyed Fabric	Explanation
Recycled-PA66 / Recycled -PA66	PPG	PPD	Both sides of the spacer are from Recycled-PA66 yarn.
Umorfil / Umorfil	UUG	UUD	Both sides of the spacer are from Umorfil yarn.
Recycled -PA66 / Umorfil	PUG	PUD	One side of the spacer is from Recycled-PA66 yarn and the other side is from Umorfil. The front side is considered as the Recycled-PA66 side.
Umorfil / Recycled -PA66	UPG	UPD	One side of the spacer is from Recycled-PA66 yarn and the other side is from Umorfil. The front side is considered as the Umorfil side.

Yarn count, breaking force and elongation of yarns were tested in accordance with ISO 2060 and ISO 2062 standards, respectively. Thickness measurements were taken under a pressure 20 g/cm<sup>2</sup> using R&B Cloth Thickness Tester according to ISO 5084. Weight of the fabrics were determined according to TS EN 12127 standard. Air permeability test was done in 20 cm<sup>2</sup> test surface area with 200 Pa pressure according to ISO 9237 standard. ASTM D 4032 was used for fabric stiffness testing. Contact angle of all samples were measured using Cam 101 contact angle goniometer (KSV INSTRUMENTS). Course and wale were measured with a magnifying glass. Water vapor permeability tests were done according to BS 7209:1990 standard.

Vertical wicking tests were applied in both course and wale directions. For the tests, 5 mm of the samples (25 mm x 200 mm) were immersed in distilled water and the rising height of the water on each side of fabric is recorded after 1 min, 5 min, 10 min, 15 min, 20 min, 25 min, and 30 minutes (Figure 3.3).



**Figure 3.3 :** Wicking test samples.

For determining the drying rates, samples with a radius of 10 cm were prepared, weighed before wetting and wetted in a beaker full of 1 liter of distilled water for 30 minutes. After hanging the samples for 15 seconds vertically, they were weighed once again (Coplan, 1953). Excess water in the samples was taken away by laying both sides of the samples on a paper towel for 2 minutes. After that, the samples were left for drying and the weight was recorded

after 30 minutes and then every hour until the weight of samples reached 105% of their dry weight. The samples were considered as dry when they reached 105% of their initial weight. The wetting percentage of samples represent the water absorption amount of samples even treated with the same removal of excess amount of water process.

Area covered by one drop of water test was done to understand transverse wicking ability of the samples (Sampath et al., 2011). Each sample was mounted on an embroidery frame and one ml of water was dropped on the fabric to measure the spreading area. The spreading of water drop was calculated with general elliptic area formula with longest distance and shortest distance of spreading area approximately.

The fabric bulk density or fabric mass density ( $\text{g/cm}^3$ ) is subject to both fabric weight and thickness. The fabric bulk density was calculated using the subsequent formula 3.1 ((Palani et al., 2019)

$$\text{Bulk density (g/cm}^3\text{)} = \text{Areal density (g/m}^2\text{)} / \text{Thickness (t)} \quad (3.1)$$

Porosity of the spacer samples, on the other hand, was also determined according to the formula 3.2 (Palani et al., 2019).

The porosity can be expressed either as a fraction or as a percentage.  $1,14 \text{ g/cm}^3$  was used for the density of the Recyled PA 66 filament and  $1,14 \text{ g/cm}^3$  was used Umorfil fimalent to calculate the porosity of the samples.

$$\text{Porosity (\%)} = [1 - \text{Fabric density (g/cm}^3\text{)} / \text{Filament density (g/cm}^3\text{)}] \times 100 \quad (3.2)$$

## 4. RESULT AND DISCUSSION

### 4.1 Yarn Properties

Tested properties of the yarns used in the production of the samples are presented in Table 4.1.

**Table 4.1 : Yarn Properties.**

Yarn Type	Yarn Count (dtex)- (CV%)	Tenacity (cN/Tex)- (CV%)	Elongation (%)- (CV%)
Recycled-PA66 S	76-(1)	37-(3)	30,76-(9)
Recycled-PA66 Z	77-(1)	35-(2)	29,63-(6)
Umorfil-PA6 Z	76-(1)	38-(3)	39,57-(6)
Umorfil-PA6 S	77-(1)	37-(3)	31,15-(4)
Monofilament PA6	19-(3)	38-(5)	51,28-(17)
Lycra	44	-	-

As can be seen in Table 4.1, the yarns used for knitting both layers of the spacer structure were of the same yarn count and had similar tenacity properties which means that all the samples can be knitted using the same knitting parameters.

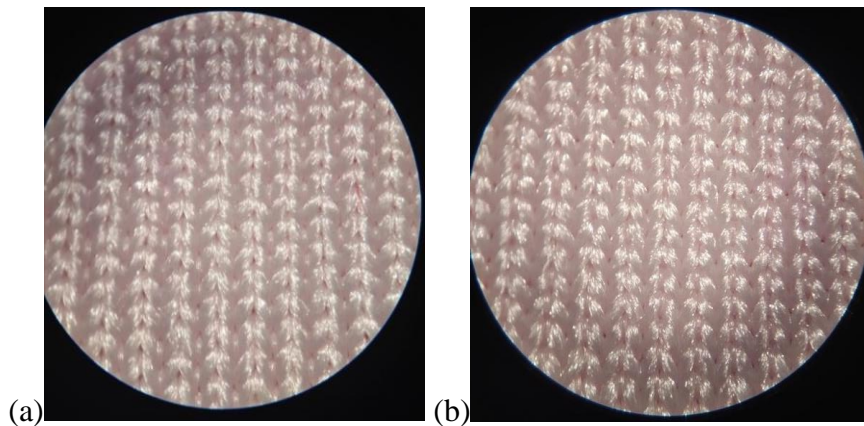
### 4.2 Fabric Properties

Constructional properties together with the stiffness of the samples are presented in Table 4.2.

**Table 4.2 : Fabric properties.**

Samples	Coarse per cm (cpc)	Wales per cm (wpc)	Stitch Density (cpc x wpc)	Weight (g/m <sup>2</sup> )	Thickness (mm)	Bulk density (g/cm <sup>3</sup> )	Porosity (%)	Stiffness (kgF)
PUG	21,6	41	902,9	404	1,36	0,293	62	1,54
UPG	21,6	41	902,0	404	1,36	0,293	62	1,63
UUG	21,8	41	902,9	405	1,34	0,298	62	1,43
PPG	22,2	41	915,8	391	1,35	0,291	62	1,56
PUD	21,7	32,8	711,8	347	0,69	0,508	43	0,36
UPD	21,7	32,8	711,8	347	0,69	0,508	43	0,29
UUD	21,6	32	682,4	335	0,68	0,49	45	0,34
PPD	21,7	31,6	694,5	346	0,65	0,536	41	0,31

In Figure 4.1, front and back side pictures of PPD fabric are presented as a representative sample.



**Figure 4.1 : Image of PPD Fabrics (a-front and b-back view).**



**Figure 4.2 :** Image of PPD fabric (on the left) and PPG fabric (on the right).

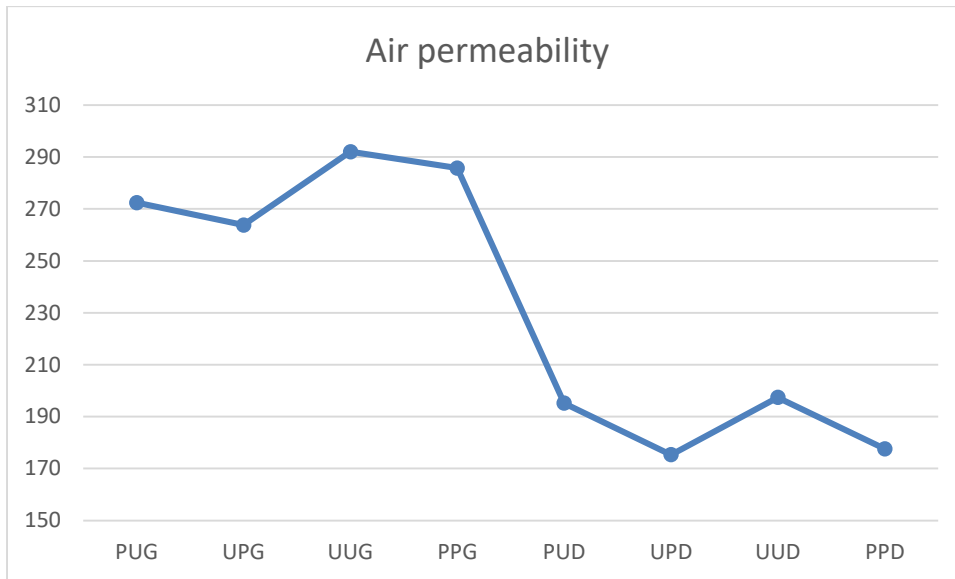
Bulk density of a fabric, which is influenced from the stitch density, is the measure of fabric weight per unit volume and also influences the porosity. The t test analysis conducted revealed that there is no statistically significant difference in 95% confidence limit for the bulk density and porosity values among the samples within the greige fabric group, and also within the dyed samples. This enabled the comparative study of the influence of fiber types on moisture related properties of the samples. The statistically significant differences between those properties of the greige samples and dyed ones are a result of the dyeing and finishing process applied.

#### 4.2.1 Air permeability test results

As was mentioned before, during water vapor and air permeability tests, for the PU samples, Recyled PA66 was considered as the outer side of the fabric, while Umorfil side was considered as the inner side. While testing the UP samples on the other hand, the fabrics were reversed. Air permeability of the samples are presented in Table 4.3 of and related graph is given in Figure 4.3.

**Table 4.3 :** Air permeability results of the samples.

Samples	Air Permeability (l/m <sup>2</sup> /s)
PUG	272
UPG	264
UUG	292
PPG	286
PUD	195
UPD	175
UUD	197
PPD	178



**Figure 4.3 :** Air permeability graph of samples.

According to one way ANOVA test conducted in order to investigate the effect of yarn type on fabric air permeability, yarn type was found to be a significant factor on air permeability properties of the samples ( $F=833$ ,  $p=0,00$ ).

As given in Table 4.3 and Figure 4.3 the air permeability of the greige samples was recorded to be higher than that of the dyed ones, which might be due the higher porosity and lower density of the undyed samples.

It was also observed that air permeability of greige and dyed samples had similar tendencies and, either greige or dyed, the samples having Umorfil layers on both sides had the highest air permeability performance.

It was observed that after the dyeing process air permeability of UUD and PUD samples as well as PPD and UPD samples converged and had closer air permeability results. For the both greige and dyed samples, the layer facing the air flow seems to determine the air permeability of the bilayered structure when the Umorfil layer faced the air flow first during testing, namely the PU samples, slightly higher air permeability values were displayed than the reversed UP samples. It might be suggested that when different fibers are used for knitting the layers of the spacer fabric Umorfil side can be used as the outer side of the clothing. This result is also compatible with the findings of Çeven & Günaydın (2021) who found that the dyed Umorfil sample in thir study provided the highest air permeability while this was not the case for the greige ones.

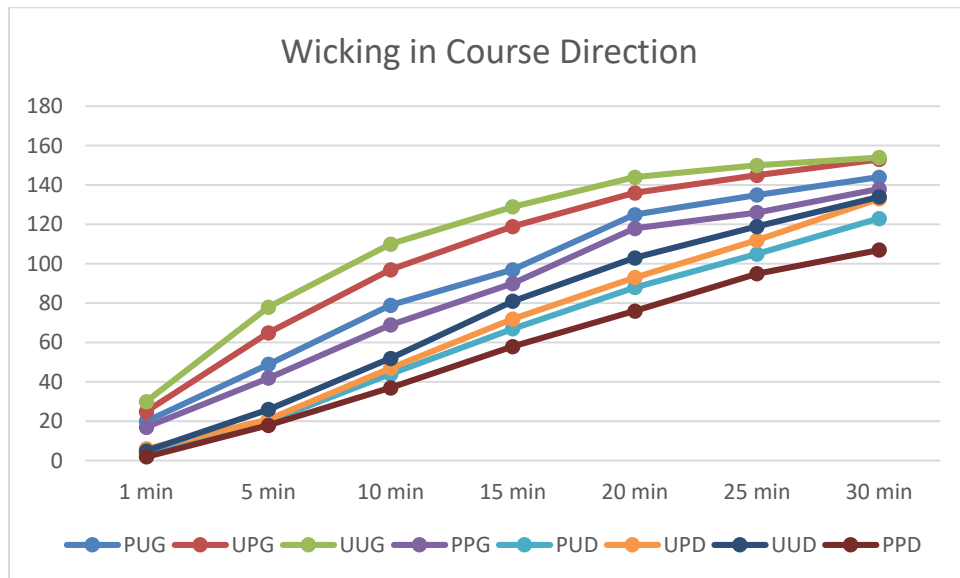
## 4.2.2 Wicking test results

### 4.2.2.1 Vertical wicking in course and wale directions

Vertical wicking of the samples in course and wale directions are given in Table 4.4 and Table 4.5. and in the related figures, Figure 4.4 and Figure 4.5.

**Table 4.4 :** Wicking heights in course direction.

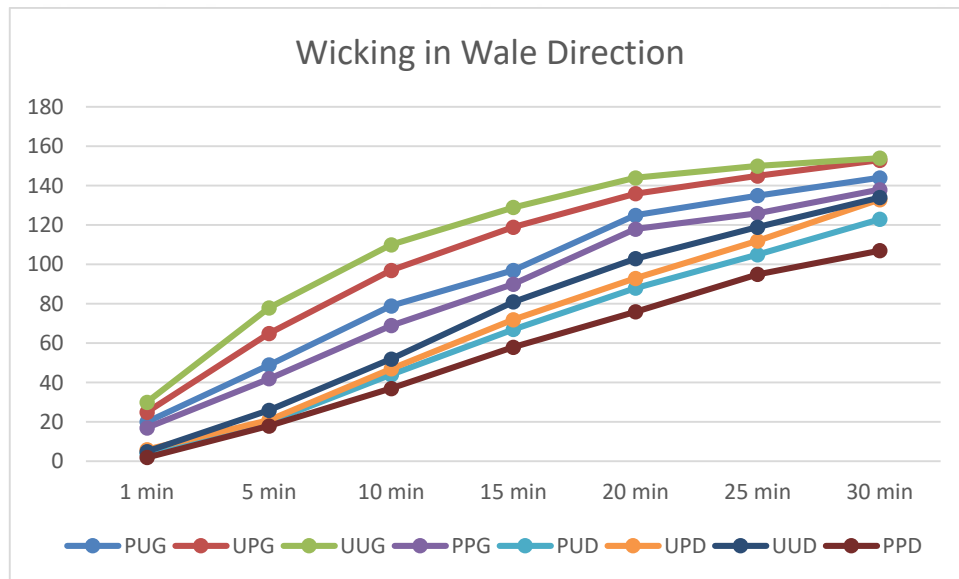
Samples/ Minutes	1 min	5 min	10 min	15 min	20 min	25 min	30 min
PUG	19	51	84	101	125	133	142
UPG	21	53	88	109	130	139	151
UUG	29	79	109	132	143	150	151
PPG	18	41	71	90	117	123	134
PUD	5	23	45	69	85	100	118
UPD	5	25	47	72	88	104	121
UUD	6	25	53	68	82	98	116
PPD	2	17	36	59	74	87	99



**Figure 4.4 :** Wicking of samples in course direction.

**Table 4.5 :** Wicking heights in wale direction.

Samples/Minutes	1 min	5 min	10 min	15 min	20 min	25 min	30 min
PUG	20	49	79	97	125	135	144
UPG	25	65	97	119	136	145	153
UUG	30	78	110	129	144	150	154
PPG	17	42	69	90	118	126	138
PUD	4	20	44	67	88	105	123
UPD	6	21	47	72	93	112	133
UUD	5	26	52	81	103	119	134
PPD	2	18	37	58	76	95	107



**Figure 4.5 :** Wicking graph in wale direction.

According to the data presented in the related tables and figures, wicking height in the greige samples has been higher than that of the dyed samples. This might be due to the higher porosity, thickness and lower bulk density of undyed samples.

Effect of different yarns used in the front and back layer of the samples on the vertical wicking performance show that the wicking rate was higher in the wale direction than in the course direction for the dyed samples while there was no difference in course and wale wicking heights of the greige ones. Higher wicking rate in wale direction of a warp spacer fabrics was also observed by Bagherzadeh et.al (2012), Prakash et.al (2019).

We observed a variation in wicking behavior of both greige and dyed samples as the fiber composition varied in the fabrics. The results showed that UUG and UUD fabrics, which had Umorefil fibers on both sides, had the highest wicking performance both in the course and wales directions. Also for the samples whose layers were knitted from different fibers, namely PUG-UPG and PUD-UPD ones, the wicking height has been higher on the Umorefil layer. The samples in which both front and back side of the fabric is the same, the wicking heights are comparable for both sides. PP samples, however, had the lowest vertical wicking performance. During wicking, water flows through inter-fiber spaces in the yarn by the interfacial tension between the liquid and the fiber surfaces. So, the rate of wicking not only depends on the spaces among the fibers in the yarn and but also on the surface energy of the fiber (Bagherzadeh et al., 2012b). Higher number of filaments in the Umorefil yarns might have resulted in higher capilarity in the yarn structure. Also, Umorefil fibers seem to contribute to vertical wicking performance due to its inherent properties.

#### 4.2.2.2 Transverse wicking

Transverse wicking of fabrics is important because the perspiration transfer from skin involves the movement of sweat through the thickness of the fabric in the lateral direction.

Transverse wicking areas of the samples after 5, 10, 15 minutes and the time the fabric needed for absorbing 1 ml water are given in Table 4.6. In Figure 4.6 wetted area of the front and back layers are presented.

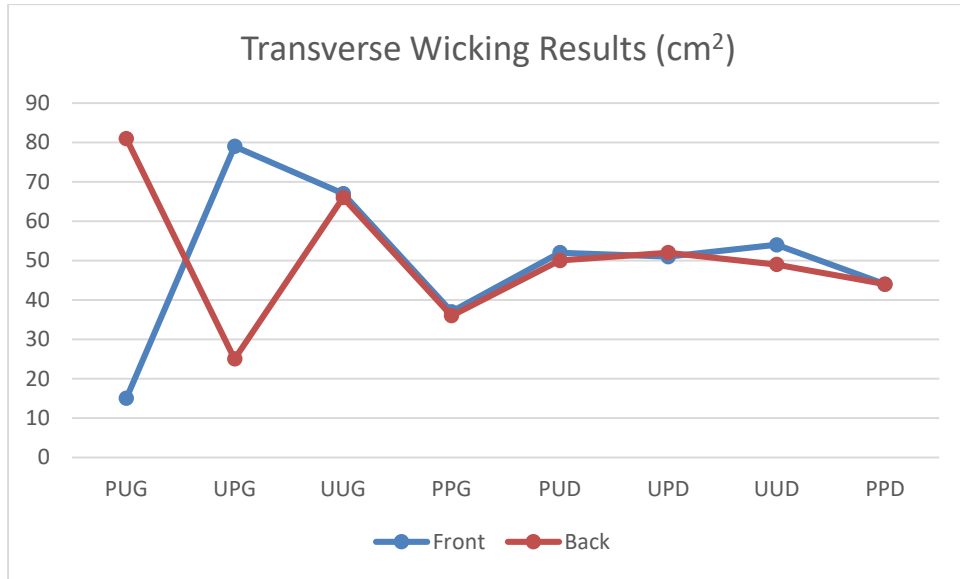
**Table 4.6 :** Transverse Wicking Results.

	Samples	Absorption time for 1 ml drop water	Wetted area after 5 min (cm <sup>2</sup> )	Wetted area after 10 min (cm <sup>2</sup> )	Wetted area after 15 min (cm <sup>2</sup> )
PUG	Front layer	19 sn	12,6	15,7	18,3
	Back layer	19 sn	70,8	87,4	89,9
UPG	Front layer	16 sn	71,4	83,8	80,9
	Back layer	16 sn	19,4	22,4	28,6
UUG	Front layer	13 sn	54,9	64,4	66,5
	Back layer	13 sn	59,7	67,3	69,5
PPG	Front layer	54 sn	20,7	34,3	43,4
	Back layer	54 sn	22,8	33	40,2

**Table 4.6 (continued) : Transverse Wicking Results.**

	Samples	Absorption time for 1 ml drop water	Wetted area after 5 min (cm <sup>2</sup> )	Wetted area after 10 min (cm <sup>2</sup> )	Wetted area after 15 min (cm <sup>2</sup> )
PUD	Front layer	3,43 min	28,6	44,4	52,4
	Back layer	3,43 min	27,8	41,1	48,1
UPD	Front layer	3,2 min	24,6	40,7	48,9
	Back layer	3,2 min	26,4	46,5	56,7
UUD	Front layer	2,52 min	19,3	47,5	53,7
	Back layer	2,52 min	17,1	44,7	49,5
PPD	Front layer	3,52 min	21,6	41,4	50,3
	Back layer	3,52 min	24,2	40,4	48,6

As may be seen from Table 4.6, the time needed to absorb 1 ml of water is much shorter for the greige samples than that for the dyed ones. This might be due to higher porosity of the samples as well as the undyed/untreated fibers' absorption behaviour. When water is dropped onto the Umorefil surface of the samples, the duration needed for absorption has been shorter. On the other hand, the wetting area on the Umorefil surfaces have been larger than the area wetted on the Recycled-PA66 layers. For the greige samples, synergistic effect of PA layer's moisture transfer and Umorefil layer's absorption capacity can be clearly seen. Accordingly, it can be inferred that when the PA layer is used next to skin, the feeling of wetness can be reduced. However, the transverse wetting performance of the fabrics leveled out after the dyeing process. Still, all Umorefil fabrics' wetting area on both sides were slightly higher than the area of all Recycled-PA66 fabrics. The higher moisture absorption capacity of Umorefil fibers (7,8 %) in comparison to PA fibers (4,7%) as well as the contact angle measurement presented in Table 4.7 supports the obtained results. Also, results obtained for transverse wetting is in harmony with the results of Soydan et.al (2020) who stated that Umorefil had higher wicking properties with lowest wetting time than 100% PA and Umorefil-Cotton combined samples.



**Figure 4.6 :** Wetted area of front and back layers after 15 min (blue points for front layer of the sample and orange points for back layer of the sample).

**Table 4.7 :** Contact angle results.

Samples	Contact angle (° degree)
PUG	110
UPG	56
UUG	55
PPG	94
PUD	97
UPD	91
UUD	84
PPD	82

#### 4.2.3 Drying rate test results

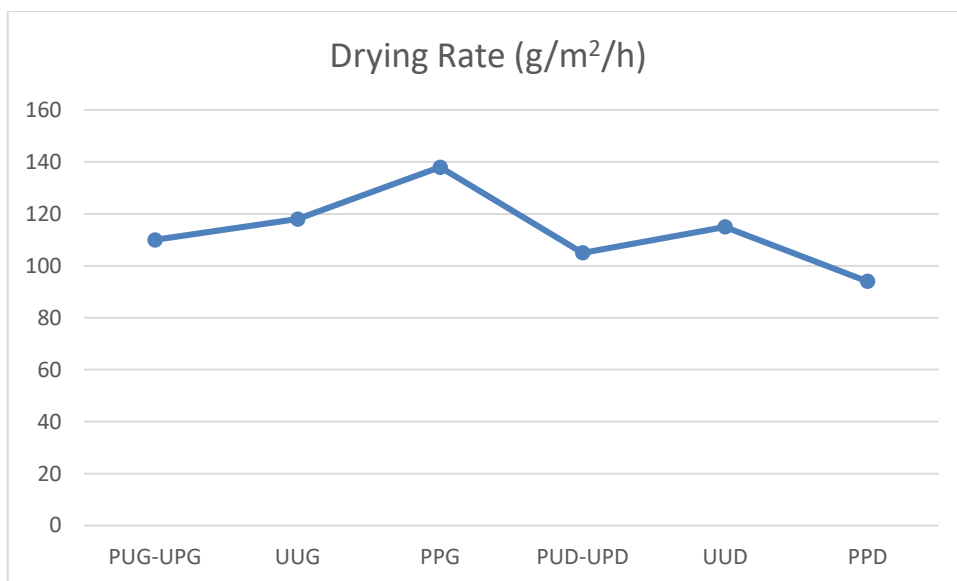
The drying rate test results are presented in Tables 4.8 and 4.9, and Figures 4.7 and 4.8. During the drying tests, it was observed that most of the samples reached 105% of their own dry weight after 3 hours except the PUG and UPG samples which dried after 4 hours.

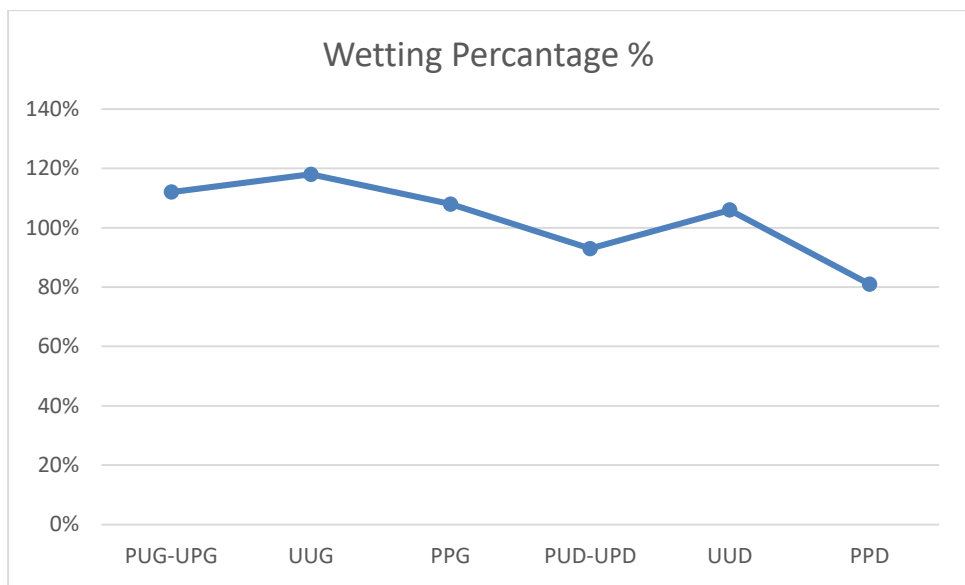
**Table 4.8 : Drying rate test results.**

Samples	Thickness of samples (mm)	Dry Weights (g)	Wetting Percentage %	After 1 hour (g)	After 2 hours (g)	After 3 hours (g)	After 4 hours (g)	Drying Rate (g/m <sup>2</sup> /h)
PUG-UPG	1,35	4,04	113%	6,18	5,4	4,58	4,07	114
UUG	1,3	4,07	112%	6,55	5,47	4,66	4,08	113
PPG	1,4	3,91	109%	5,74	4,84	4,06	-	137
PUD-UPD	0,69	3,47	92%	4,62	3,79	3,4	-	108
UUD	0,71	3,33	101%	4,46	3,74	3,36	-	112
PPD	0,63	3,41	77%	4,33	3,62	3,43	-	87

**Table 4.9 : Wetting percentage of samples.**

Samples	Wetting Percentage %	Drying Rate (g/m <sup>2</sup> /h)
PUG-UPG	112%	110
UUG	118%	118
PPG	108%	138
PUD-UPD	93%	105
UUD	106%	115
PPD	81%	94

**Figure 4.7 : Drying rate results of samples.**



**Figure 4.8 :** Wetting percentage results of samples.

When the samples are examined, it is seen that the greige samples absorbed more water than the dyed samples and the ones that have Umorfil in their structure, either on both sides or on one side, had higher wetting percentage. This is comprehensible when moisture absorption capacity of the fibers are considered.

Considering the drying rates, similar results were observed in UUG and PUG-UPG samples due to the Umorfil structure.

The highest drying value in greige samples were seen in the PPG sample. It can be concluded that Recycled-PA66 fiber tends to dry faster than Umorfil because although they have similar wetting percentages and the drying rate of PPG were higher than that of UUG.

The PPD samples showed the lowest drying rate in the dyed samples, but considering that all dyed samples dried within 3 hours, the reason for lowest drying rate of PPD sample might be related to the lowest wetting percentage. It was seen that the water absorption ability of the fabrics affected the drying speed.

With the fact that all dyed samples dried within 3 hours, Umorfil samples hold more water and evaporate faster. These properties of Umorfil yarn might be used in the outside of the product to absorb sweat transferred by the PA layer.

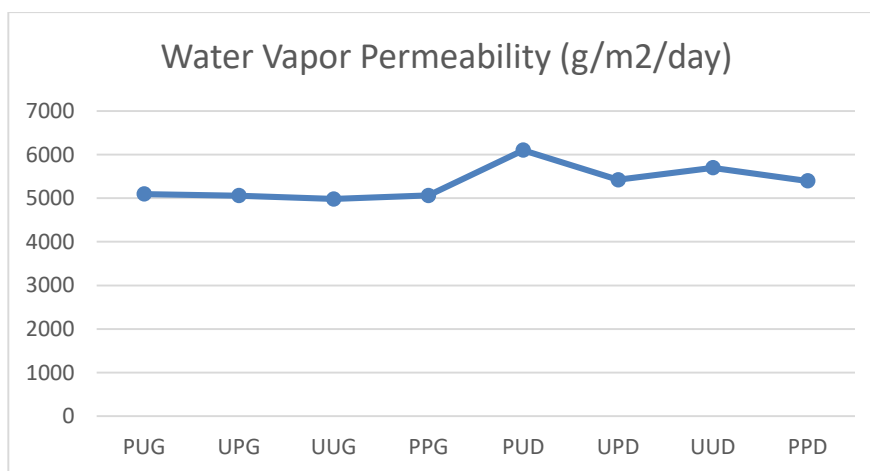
#### 4.2.4 Water vapour permeability test results

Water vapour permeability of the samples, which is an indication of the ability of fabrics to transfer water vapour from the skin to the outer surface, are presented in Table 4.10 and the Figure 4.9. The water vapor permeability behaviour allows for the escape of water vapor, thus for the comfort of spacer fabric, the better WVP, the higher comfort for wearer.

As may be seen from the Table 4.10 and the Figure 4.9, the dyed samples had higher WVP than the greige ones did, which is an opposite behaviour observed for air permeability results.

**Table 4.10 :** Water Vapor Permeability results.

Samples	Water Vapor Permeability (g/m <sup>2</sup> /day)
PUG	5095
UPG	5058
UUG	4983
PPG	5063
PUD	6103
UPD	5421
UUD	5696
PPD	5395



**Figure 4.9 :** Water vapor permeability test graphs.

Water vapour transmission takes place not only through the air spaces among the yarns but also through the structure of the fibres and depends on the moisture absorption capacity and hygroscopic properties of the constituent fibres (Soares et al., 2018). Umorfil® N6U is a bionic nylon fiber with higher moisture regain in comparison to regular nylon fibers (*Umorfil Launches New Revolution in Nylon 6*, n.d.). The differences in moisture absorption capacity of the fibers are expected to influence the WVP of the samples. For the greige fabrics the lowest water vapour transmission was recorded for the UU fabrics where for the dyed ones this tendency diminished and PUD sample allowed the highest vapour transmission.

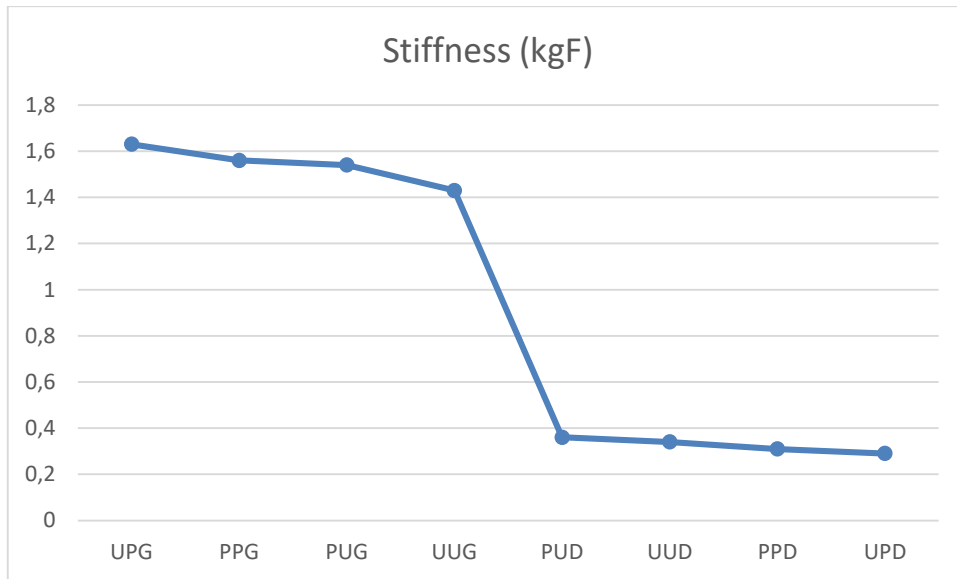
Rajan et.al (2016) stated in their study that WVP behaviour of spacer fabric were correlated with wicking behaviour. Therefore, in this study, the highest and faster wicking behavior observed for the Umorfil samples might have supported the results obtained for WVP of dyed Umorfil samples.

#### 4.2.5 Stiffness test results

The stiffness results are presented in Table 4.11 and the Figure 4.10.

**Table 4.11 : Stiffness results.**

Samples	Stiffness (kgF)
PUG	1,54
UPG	1,63
UUG	1,43
PPG	1,56
PUD	0,36
UPD	0,29
UUD	0,34
PPD	0,31



**Figure 4.10 :** Stiffness of samples.

Finally, the samples were tested for determining their stiffness. Although the stiffness of the samples did not differ according to the fiber type used in the bilayered fabric surfaces, dyed samples with lower thickness values showed lower stiffness values. Low rigidity might be caused by dyestuff and dyeing chemical action.

### 4.3 Cost Analysis

The costing results showed in Table 4.12 that fabrics with Recycled-PA66 were cheaper than all samples due to the price of Recycled-PA66 yarns being cheaper than Umorefil yarns. The most expensive fabric was UUD with 20 euro/kg. When the fabric was produced with one face Umorefil and one face Recycled-PA66 as PUD and UPD samples, the price was in the range between the price of PPD and UUD fabrics with 18,8 euro/kg. There will be cost saving with moisture comfort properties using PUD and UPD fabrics.

**Table 4.12 :** Fabric Price List.

Samples	Price (Euro/kg)
PUD	18,8
PPD	18
UUD	20

## 5. CONCLUSION

Sustainable fibers, namely Recycled-PA66 and a biodesigned fiber-PA6 Umorfil, were used to produce bilayered knitted fabrics that are intended to be used in sportswear apparel having improved moisture related properties. In order to study the moisture related comfort characteristics of the fabrics namely, air permeability, wicking performance, drying rate, water vapor permeability, stiffness and cost were analyzed. According to the results obtained;

- It was observed that fabrics containing Umorfil could not maintain some of the greige properties after dyeing and finishing processes.
- Air permeability results of both dyed and greige Umorfil samples were similar. Umorfil allowed slightly higher air permeability than Recycled-PA66, thus Umorfil can be better as the outer layer of the clothing for air permeability.
- Umorfil fibers have proved to be superior in terms of vertical wicking of water due to its inherent properties.
- Umorfil has the fastest absorption time in both greige and dyed samples and the water absorption rate of Recycled-PA66 can be improved with combining with Umorfil in spacer structure.
- The transverse wicking results showed that using Recycled-PA66 on the inside can reduce the feeling of wetness as it seems to direct water to Umorfil side easily.
- Umorfil samples hold more water and evaporate faster. These properties of Umorfil yarn might be used in the outside of the product to absorb sweat transferred by the PA layer.
- The fabric price of PPD is cheaper than UUD samples. The price of fabric with one face Umorfil and one face rcy-PA66 was in the range between the

price of using only one of them, thus there will be cost saving with improved moisture comfort properties using PUD and UPD fabrics.

To sum up, comfort properties of fibers can be used in different parts of the garments depending on the intended use and purpose. Making the inner side of fabric from Recycled-PA66 and the outer side from Umorfil gives cost saving production with improved comfort properties. Also, these two different fibers combining in spacer structure allows to combine superior properties of both Umorfil and Recycled-PA66 fibers.



## **6. SUGGESTIONS FOR FUTURE STUDIES**

Depending on the results, Umorfil-Rcy PA66 fabrics were appreciated with their improved moisture properties such as price reduction and improved comfort properties. In future studies, different bulk structures and moisture properties can be examined in with different thickness and different regenerated fibers.

In addition, the thermal properties and surface properties of these fabrics, whose moisture comfort properties we have examined as circular weft knit, can be examined in terms of thermal comfort by adding thermal tests and the clothing comfort properties which can be examined by using thermal manikin or by live trials of the clothes to be sewn.

Modification of conventional dye-treatment processes for fabrics containing Umorfil can be recommended in order to give maintaining structural and comfort properties to Umorfil fabrics.

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### PUBLICATIONS, PRESENTATIONS AND PATENTS ON THE THESIS:

- **Karabulut, A. B., Nergis, F. B., & Candan, C.** (2022, December). Development of Bilayered Knitted Fabrics from Sustainable Fibers For Sportswear Applications. 4<sup>th</sup> International Eurasian Conference on Engineering and Technology.