



**TEKSTİL BİLİMLERİ VE MÜHENDİSLİĞİ
ALANINDA BİLİMSEL ARAŞTIRMALAR**

Editör: Prof.Dr. Suat CANOĞLU

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Tekstil Bilimleri ve Mühendisliđi Alanında Bilimsel Arařtırmalar

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**Tekstil Bilimleri ve Mühendisliği
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Editör: Prof.Dr. Suat CANOĞLU

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"Bu kitapta yer alan bölümlerde kullanılan kaynakların, görüşlerin, bulguların, sonuçların, tablo, şekil, resim ve her türlü içeriğin sorumluluğu yazar veya yazarlarına ait olup ulusal ve uluslararası telif haklarına konu olabilecek mali ve hukuki sorumluluk da yazarlara aittir."

SEAM PERFORMANCE PROPERTIES OF TEXTILE PRODUCTS AND AFFECTING FACTORS

Ayşe ŞEVKAN MACİT¹

1. INTRODUCTION

A seam must have an aesthetically pleasing appearance. Furthermore, the seam is expected to deliver high technical performance. Seam performance is crucial for garment performance and quality. When discussing seam performance, various characteristics come to mind. These characteristics, which are frequently evaluated, include seam strength, seam elongation, seam puckering, seam efficiency, seam slippage and seam grinning, seam damage and sewability property. Various factors influence seam performance properties. Among the primary factors affecting seam performance are fabric properties and sewing properties. This chapter examines seam performance properties and also fabric properties and seam properties that influence seam performance, as well as previous studies on these properties.

2. SEAM PERFORMANCE PROPERTIES

Sewing is the process of decorating larger combined pieces or three-dimensional articles by joining two or more materials together (Coats, 1998). Sewing quality is not just about the appearance of the seam; it can be determined by various

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characteristics. Certain characteristics are evaluated in determining seam performance, and objective and/or subjective standard methods are used to evaluate these characteristics.

2.1. Seam Strength and Elongation

Seam strength is defined as the resistance of the seams against breaking when a force is applied perpendicular to the seam direction in sewn fabrics; and the elongation at break is defined as the percentage elongation value of the seam when it breaks (Gürarda, 2005). In other words, seam strength is the degree of tensile force required to break the weakest stitch in a seam. Seam strength is related to loop strength and stitch tension (Onur, 2009).

Seam strength is an important property for seam performance. It's known that seam parameters affect seam strength and elongation. Stitch density, stitch and seam type and needle and thread properties are also related to seam strength, so careful attention should be paid to fabric compatibility when determining these factors. Fabric parameters also affect seam performance. Fabric raw material, construction, and weight can all affect seam performance.

On the other hand, the selected stitch, thread, and fabric must be compatible in terms of elongation. Any further fabric elongation will cause the thread and stitches to break. Seam elongation is affected by the properties and tension of sewing thread, stitch and seam type, stitch density and fabric properties (Bayraktar, 2005).

Stitch types have different elongation property. While chain stitch and lockstitch are compared, chain stitch exhibits greater elongation than lockstitch. Stitch density is a key parameter in determining stitch elongation, but simply increasing stitch density does not increase stitch elongation. In cases where

stitch length is short, sufficient elongation can be achieved by reducing the tension setting (Bayraktar, 2005).

2.2. Seam Efficiency

Seam efficiency is another important characteristic for seam performance. It varies depending on seam strength and fabric strength. Seam efficiency can be calculated as shown Eq. (1) below (Rajput et al., 2018). Therefore, it can be said that seam efficiency is affected by all factors affecting seam strength and fabric strength.

$$\text{Seam Efficiency} = (\text{Seam Strength} / \text{Fabric Strength}) * 100 \quad (1)$$

About seam efficiency, it is stated that 60-80% seam efficiency is common, but 80-90% seam efficiency is difficult to achieve (Gürarda, 2019).

2.3. Seam Slippage and Seam Grinning

If the fabric on both sides of the seam becomes distorted and the fabric yarns slip through the seam, creating an opening in the fabric, seam slippage occurs, and this depends mainly on the structure of the fabric (Coats, 1998).

Seam slippage occurs when the fabric on both sides of the seam deforms and the fabric threads slip through the seam, creating an opening in the fabric; this condition primarily depends on the fabric's structure.

Some fabrics are more prone to seam slippage than others; while this problem doesn't occur in knitted fabrics, it's different in woven fabrics. Fabrics woven with low warp and weft density are particularly prone to seam slippage due to the greater freedom of movement of the thread. In low-density fabrics, seam slippage can occur if a seam is created close to the edge. The slipperiness of the fabric yarn or the application of a lubricant or softener to

the fabric, which allows for freer thread movement, can affect seam slippage (Coats, 1998).

When two pieces of fabric are joined with a seam, and the fabric is forced at a right angle to the seam, a gap forms between the two pieces before the seam breaks. It is seam grinning. Seam grinning can be controlled by seam tension and density (Coats, 1998).

2.4. Sewability

Needle penetration force affects seam efficiency and the high level of force means high fabric resistance and high risk of damage (Gürarda, 2008). L&M sewability tester measures the needle penetration force without using sewing thread, in gf, via a threshold value determined according to fabric weight. The device counts the number of needle penetration forces exceeding the threshold value within 100 needle penetrations and reports them as a percentage (Gülşen Bakıcı, 2017).

To improve sewability, optimization must be achieved between stitch length, thread tension, thread-fabric properties, sewing machine features. Furthermore, the most appropriate fabric finish treatments, fabric structure and sewing parameters must be selected to achieve optimal needle penetration force (Gürarda, 2005).

2.5. Seam Puckering

One of the most important issues in sewing is seam puckering. This wavy effect, caused by strain or tension, results in seams that curl and are shorter than the fabric's cut length, creating a puckered appearance and wrinkles. Factors affecting seam puckering include the type of thread used in weaving, twist differences, finishing treatments applied to the raw fabric, sewing machine type, conditions during sewing process, and properties of sewing thread (Korkmaz, 2007). Additionally, unavoidable

puckering during sewing, puckering due to feeding, tension puckering, and shrinkage of threads and fabrics due to washing can all cause to seam puckering (Karazincir, 2014).

There are many techniques measuring seam pucker. Eq. (2) shows calculating seam pucker percentage (Hati and Das, 2011).

$$SP \% = (L2-L1) / L1 \times 100 \quad (2)$$

SP % = seam pucker percentage, L1 = sewn fabric length and L2 = unsewn fabric length.

2.6. Seam Damages

Seam damage affects seam performance with reducing seam strength and occurs due to thermal and mechanical damages. The high needle temperature during sewing process causes thermal damage to the fabric. The heat is transferred to other parts of the sewing machine, the fabric, and the sewing thread (Gürarda, 2019). Sewing speed, needle size, needle point shape, fabric density, fabric finishing processes and sewing thread are important factors causing thermal damage (Thilagavathi and Viju, 2013).

Mechanical damage is damage that affects the aesthetics and performance of apparel. Fabrics can be mechanically damaged during sewing (Gürarda, 2019).

3. FACTORS AFFECTING SEAM PERFORMANCE

3.1. Sewing Properties Affecting Seam Performance

In this section, sewing properties that are considered important for seam performance are included.

3.1.1. Stitch and Seam Types

Seam and stitch types are important parameters in joining garment and affect its quality, comfort and fitness properties (Admassu et al., 2022). Inappropriate stitch types and seam types affect seam performance negatively (Gürarda, 2019).

There are a wide variety of stitch types and seam types used in sewing process. Therefore, the importance of selecting the proper stitch and seam type for the fabric can be emphasized. Studies presented in the following sections demonstrate that the stitch types and seam types chosen affect seam performance in various ways.

3.1.2. Stitch Density

Stitch density is the number of stitches per unit length (stitches per inch - SPI) in a stitch. More stitches per unit length generally means higher stitch quality. The average stitch length is stated as 2.5 mm with typical setting on sewing machines (Gürarda, 2019). The number of yarn interloops on the surface of the sewn fabric in 1 cm gives stitch per cm (Spcm). It is stated that the appropriate spcm selection affects seam performance (Ghani, 2011).

3.1.3. Seam Allowance

Seam allowance is defined as the area between the edge of the fabric and the stitch line and the preferred seam allowance is determined by the pattern, design and fabric requirements. It can vary from 6.4 mm (1/4 inch) to several inches and the generally considered standard seam allowance is 1.5 cm (5/8 inch) (Gürarda, 2019).

3.1.4. Sewing Thread

Stitches are formed by using threads, thus holding garment pieces together. Sewing thread parameter is an important factor in apparel manufacturing process. While sewing thread has

a very low weight in the garment, on the other hand it is of great importance in terms of garment quality (Farhana et al., 2015a).

The desired stitch formation properties from sewing thread can be listed as; not breaking at high sewing speed, creating a continuous and regular stitch, not causing skipped stitches, being resistant to wear caused by needles and other machine parts and causing minimum damage to the fabric (Coats, 1998).

Selecting the most appropriate thread for the fabric is crucial to achieving the desired appearance and performance. A good sewing thread should possess the following characteristics: lubrication, balanced twist, abrasion resistance, strength, and friction (Çetiner, 2006). It is stated that mechanical properties of sewing thread, such as tensile strength, friction, dimensional stability, and bending are related to seam quality. Among these mechanical properties, the primary requirements for sewing threads are high strength, high modulus, uniform frictional properties, and abrasion resistance. High-strength sewing threads will provide high seam strength (Mandal and Abraham, 2010).

To improve sewing performance, improvement methods should be investigated during the manufacturing stage. Therefore, the performance of sewing threads should be examined before sewing, and proper settings should be made. In other words, these inspections should begin while the garment is still in manufacturing (Bayraktar, 2005).

A good stitch quality can be achieved when a thread with good strength, elongation and recovery behavior is sewn onto a suitable fabric, with the appropriate thread size and sewing machine setting (Ghani, 2011).

3.1.5. Sewing Needle

The needle has basic functions such as opening a hole in the fabric through which the thread can pass, carry the needle thread through the fabric, form a loop in lockstitch machines, pass the thread through the loop in other than lockstitch machines (Ghani, 2011).

Needle selection is crucial for stitch quality, and it must be appropriate for the fabric type, stitch type, thread, and machine. Improper needle shape and size will cause sewing fault. Needle size has a major effect on stitch damage. If a needle is too thin for the fabric and thread being sewn, it will bend and break during sewing. Conversely, if the needle is too thick, it will cause damage to the threads as it passes through the fabric, skipped stitches, poor stitch appearance, and fabric damage (Bayraktar, 2005).

3.1.6. Stitch Direction

Stitch direction affects seam performance properties, as well as other stitch parameters (Yıldız and Pamuk, 2021, Bansal et al., 2021). There are many literature studies on this subject, and the studies presented in the following section show that stitch direction affects various seam performance characteristics.

Because textile fabrics are anisotropic, their mechanical properties vary depending on direction. So fabric strength and seam strength vary at different angles, which is important for garments (Öztaş and Gürarda, 2023).

3.1.7. Sewing Speed

While high sewing speed might seem like a factor that reduces working time, it is actually a significant cause of needle heating problem. This needle heating, resulting from high sewing speed, can lead to numerous problems and damage to the stitching

process, and high sewing speed is one of the major causes of needle peak temperature (Li, 1998).

As sewing speed increases, friction between the needle and fabric increases, resulting in more heat being released per unit of time, leading to significant increases in needle temperature (Bayraktar, 2005). It is also known that increased temperature can lead to thermal damage (Thilagavathi and Viju, 2013).

3.1.8. Needle Thread Tension

Needle thread tension is a factor considered in terms of seam quality (Yıldız and Pamuk, 2021). Improper needle thread tension can cause various problems about seam performance. It is stated that the parameters such as type of sewing thread, lubricant type and feeding rate affect needle thread tension (Koncer et al., 2014).

3.1.9. Previous Studies Examining Seam Performance Depending on Sewing Properties

While studies on seam performance typically focus on a single sewing parameter, many studies evaluate multiple parameters simultaneously. Some studies investigate the impacts of sewing parameters on seam performance, conduct statistical analyses, and some of them present prediction and modeling studies.

Among the studies including the effects of seam thread properties on seam performance; Birkocak (2022) evaluated seam performance of traditional fabrics by using two different needle size and sewing thread. The researcher reported that sewing thread and fabric type had important impact on seam properties and needle penetration force values were affected by needle type. In another study, Tiber and Yılmaz (2022) investigated the effects of sewing thread and stitch type on seam properties in their study. The researchers reported that seam strength values of polyester

core spun polyester sewing thread were higher than the other sewing thread type and they also reported the values were higher in weft direction, chain stitched samples and high stitch density. Farhana et al. (2015a) investigated the effects of sewing thread linear density and seam type on seam performance of cotton twill fabric. The authors observed that lapped seam strength loss is lower than superimposed and the values are better for Tex60 than Tex105. Akter and Khan (2015) investigated the effect of sewing thread types and stitch types on seam performance and they reported that polyester-wrapped threads with a polyester filament core thread has better seam strength and efficiency than the other thread types and the researchers compared the stitch classes based on seam performance. Meriç and Durmaz (2005) evaluated sewing thread structure and lubrication ratio in terms of seam performance and the authors reported that the core-spun thread structure showed high resistance against the seam opening and also the authors found out that the threads structure affected the seam strength and they also reported lubrication ratio didn't affect seam strength. Dal and Yıldız (2014) studied with the poplin and gabardine fabrics to obtain the optimum seam performance by the parameters sewing thread type, stitch type, seam density and sewing needle type. It can be seen from the results that the parameters of seaming process effect the seam performance in this study. Yıldız and Pamuk (2023) investigated the impacts of sewing thread, sewing process, and washing on sewing performance. They found that sewing thread strength positively affects seam strength, and the effect of washing process on seam strength varies depending on the thread content.

It can be shown among the results of many other studies about the effects of sewing thread type that; sewing thread type is effective on seam pucker (Dobilaite and Juciene, 2006); sewing thread with finer count will show higher seam strength and chain stitch will show higher seam strength than lock stitch (Islam et al.

2022a); lapped seam strength loss is lower than superimposed and sewing thread linear density Tex 60 shows better seam strength result than Tex 105 (Sivakumar 2015); sewing thread has a significant effect on seam properties and thread tension has a significant effect on seam properties, (Hafez Mohamed and Hassan 2014); sewing thread type affects elongation (Çitoğlu and Kaya 2011); raw material content and count of seam thread is important on seam strength (Barbulov-Popov et al 2012a); stitch density and sewing thread type have great effect effect on seam strength (Barbulov-Popov et al., 2012b).

When the studies including needle properties were examined; Yassen (2017) investigated the needle size and also thread count, stitch density and fabric characteristics on seam strength. The author observed that sewing needle size had a positive and important effect on seam strength. The relationship between seam strength and sewing thread count were found to be in the linear form and also increasing stitch density increased the seam strength. In another study about sewing needle property, Seif (2014) used two needle size and also studied different fabric properties, seam direction, stitch type and length based on the seam slippage. The author presented that sewing in bias's direction avoided the failure of the seam slippage generally and sewing factors have important impacts on seam slippage. In a study examining needle property, Choudhary and Goel (2013) evaluated sewing needle parameters and also blend composition, sewing thread size on garment seam performance and they reported that seam strength efficiency was low at high needle thread tension and seam puckering and seam strength efficiency increased due to increasing sewing thread linear density. Gümüştaş et al. (2022) evaluated the damage due to sewing needle and examined the effects of different parameters on seam performance. The researchers decided suitability of the needle

parameter in sewing according to appearance of the fabric after sewing and evaluated the other parameters.

Within the scope of studies about sewing thread tension; Joshi et al. (2018) evaluated the fabric elongation and stitch thread tension. The results demonstrated that seam puckering was affected material quality, sewing machine and skills of operator and also they reported that high sewing thread tension in fabrics increased the tendency for seam puckering.

When examining studies based on stitch density; Rogale et al. (2012) evaluated seam performance in terms of needle size and stitch length with cotton, viscose and polyester fabrics. It was observable that these parameters were effective on seam performance and optimal needle size and stitch length were stated according to fabric type. Chen et al. (2021) investigated stitch density with shirt fabrics by using different sewing threads and seam types in terms of seam puckering. From the study carried out, it was shown that seam pucker increased as the breaking elongation of sewing thread increased. Stitch density and seam type were reported as the factors that have the least effect on seam pucker. Seam type had greater impact on fabrics prone to seam pucker. In another study, Kabir et al. (2018) researched the effects of seam parameters on seam performance with blended fabric with different structures like plain, twill, satin. The researchers reported that increasing SPI (stitch per inch) increased the seam strength and also as stitch per inch increased aesthetic look seam puckering was good. Milosavljevic et al. (2025) studied about seam strength in terms of stitch density with three different fabric thread densities per weft as well as three different linear densities of weft threads. The results demonstrated that seam strength increased due to increasing stitch density, weft thread density, and weft linear density. Chowdhary and Poynor (2006) evaluated the effect of stitch density on seam performance and they reported that stitch density influenced seam strength and elongation.

When looking at the research carried out specifically on stitch and seam types; Öztaş and Gürarda (2023) searched seam performance with wool fabrics. The authors noted that using different seam types and different angles leads to different seam strength and efficiency. Rajput et al. (2018) evaluated seam strength and efficiency for cotton fabrics. The authors observed that seam strength and efficiency differed for two different thread. Fabric type and their structural properties had significant impact on these results. Interlock fabric seam strength was higher than the others. In another study, Islam et al. (2020) investigated the seam performance of cotton fabrics with different stitch types and sewing threads. The researchers stated that seams containing more stitches per inch demonstrate more seam strength and efficiency upon different stitch structures like lockstitch, three thread flatlock stitch, four thread overlock stitch and chain stitch. Seif (2016) studied the effects of seam parameters like seam types, stitch length and rows on seam performance with wool fabrics and reported the highest values of the seam properties were seen in SSw and then LSq and SSa-1. Akram et al. (2022) studied with linen fabrics to investigate the effects of seam types superimposed, lapped and bound on seam performance by using different stitch length and stitch type. The authors revealed that seam strength and seam slippage are affected by the seam type, stitch type, and stitch per inch. Islam et al. (2019a) researched seam performance of twill fabric of two different GSM and construction with two types seam. According to the results, it was stated that seam strength and seam slippage were dependent on the thread density and GSM of the fabric. It can be concluded that lapped seam for both sample is the most effective in terms of seam properties. Raj and Devi (2017) studied with nylon canopy fabrics to analyse seam breaking force and the seam efficiency by the parameters types of weave, stitch density, stitch type and seam direction and they noted that the seam strength also varied significantly with the interactions of the primary parameters as

affected by the primary parameters. Naeem et al. (2014) investigated the effects of superimposed seam and lapped seam at different sewing speeds on seam strength and they stated that superimposed seam was superior than lapped seam in terms of seam strength and a linear relationship was determined between sewing speed and seam strength.

There are studies investigating seam performance of especially denim fabrics in terms of stitch type (Ateş et al., 2019), sewing thread type (Hossain et al., 2023), needle size, fabric weight and number of fabric layers (Haghighat et al., 2014), seam threads linear density and stitch density (Malek et al. 2019), stitch density and sewing thread count (Tuteja and Sen, 2019), sewing thread types and washing process (Ünal and Baykal, 2018).

Apart from all these studies; seam performance studies have been conducted using ultrasonic seams, a preferred method for garment joining other than conventional seam techniques. These studies evaluated seam performance properties using various parameters. The researchers analysed seam strength in terms of seam type and fabric type (Şevkan Macit and Tiber, 2018; Şevkan Macit and Tiber, 2022), ultrasonic welding parameters (Hussen et al., 2022; Raja Balasaraswathi and Bajpai, 2024).

Studies evaluating seam performance also reveal prediction and modeling studies. These studies use data from various fabric and seam properties to derive models and estimates of seam performance. In these studies, input parameters for prediction and modelling of seam performance properties are thread linear density and stitch density (Sarkar et al., 2021; Khalil and Akter, 2024), stitch density (Islam et al., 2022b), seam density per cm, the stitch type, sewing yarn type and sewing needle type (Yıldız et al., 2013), polyester ratios of fabric, stitch

density, sewing needle size and sewing thread count (Nassif and Ali, 2018).

3.2. Fabric Properties Affecting Seam Performance

In this section, fabric properties that are considered important in terms of seam performance are included.

3.2.1. Fabric Raw Material Properties

The basic materials for garments are fabric and sewing thread. In this respect, they have great importance. The raw material properties of the fabric also affect seam performance (Sülar et al., 2015; Yıldız and Pamuk, 2021). Seam performance can vary depending on the properties of the raw material. The studies reviewed in the next section also demonstrate that raw materials have different effects on seam performance properties.

Today, sustainability has a great importance and many improvement efforts are being carried out in the textile industry in this regard. From this perspective, the use of sustainable materials as raw material is also noteworthy and the use of such raw materials has been increasing in recent years. Evaluations of the use of these types of raw materials in terms of seam performance are also available in the literature (Özbeş and Gürarda, 2025).

3.2.2. Fabric Construction

Fabric construction is another factor affecting seam performance. Properties such as weave type, fabric weight, warp-weft density have a significant impact on seam performance (Yassen, 2017; Admassu, 2022; Iftikhar et al., 2018; Megeid et al., 2016). These properties affect mechanical properties of the fabric, as well as seam strength and different seam performance characteristics. Similar fabrics with different constructions will have different seam performances when evaluated from this perspective.

3.2.3. Dyeing and Finishing Treatments Applied to Fabrics

In dyeing, finishing department, fabrics are subjected to pretreatment, dyeing, printing processes. If necessary, finishing treatments are applied to the fabric to gain certain properties for final use. Fabric finishing treatments affect sewing performance (Yıldız and Pamuk, 2021). Parameters such as time and concentration in these processes may result in different sewing performances for different fabrics and sewing parameters. Studies have also shown that processes such as bleaching and dyeing affect the seam performance properties of the fabrics (Şevkan Macit, 2024; Şevkan Macit, 2025).

3.2.4. Fabric Structural and Mechanical Properties

Fabrics have certain structural properties. Structural properties of fabric such as thickness and number of layers can impact seam performance (Yıldız and Pamuk, 2021). The increase or decrease in the values of these properties or the change of these properties while other properties remain constant may affect the sewing performance in different ways.

On the other hand, fabric properties such as strength, extensibility, and bending rigidity are also among the properties that can affect sewing performance. Fabric strength is a property that directly affects sewing efficiency, which is determined by the ratio of fabric strength and seam strength (Rajput et al., 2018).

The extensibility of the fabric also affects sewing performance it is closely related to the sewing process. Low or high extensibility can cause problems during sewing processes. Generally, the higher the extensibility, the more difficult the sewing (Hui et al., 2007).

Bending rigidity of fabric is related to its stiffness and drape. The stiffer the fabric, the higher its bending rigidity. This

fabric characteristic also affects sewing performance. It can be stated that; for proper handling and manufacturing a good seam appearance, fabric should have a moderate bending rigidity (Ghani, 2011).

3.2.5. Previous Studies Examining Seam Performance Depending on Fabric Properties

The influence of fabric properties on seam performance have been investigated in many studies. Studies have examined the relationship between seam strength, seam elongation, seam puckering, seam slippage, sewability and seam efficiency with fabric properties. When examining the effects of fabric properties on seam strength, the following results are highlighted; Yassen (2017) studied seam strength in terms of fabric (yarn count and weft density) and also seam characteristics (stitch density, thread count, sewing needle size) and reported that seam strength is significantly and positively affected by both seam properties and fabric properties. In the studies about seam strength and seam efficiency, Özbey and Gürarda (2025) investigated seam performance of conventional and organic cotton woven fabrics that have different weight, yarn count in weft and warp direction and dyeing process. The authors revealed that fabric weight and conventional or organic cotton dyed with reactive dye and natural dye were effective on fabric breaking strength, seam strength and efficiency. In another study, Islam et al. (2018) researched seam strength and efficiency with cotton plain, twill and satin fabrics by using different sewing parameters and they stated that twill fabric demonstrated highest seam strength and plain fabric highest seam efficiency because of more binding point of plain fabric. It was also reported that satin fabrics had low seam strength and seam efficiency due to dimensional instability. Kara (2022) investigated the seam performance of nonwoven fabrics with different unit masses and lock stitch with different stitch length. The author found out that unit mass of the nonwoven was

not determined to be an important factor for seam strength. When other studies are examined about seam strength and efficiency; it is seen that fabric weave design and their seam designs are affective on seam strength and efficiency (Iftikhar et al., 2018), fabric raw material has an impact on seam efficiency (LaPere, 2006; Bansal et al., 2021) and on seam strength (Bansal et al., 2021), fabric types and structural properties have effect on seam strength and efficiency (Admassu, 2022) and weave construction is effective on seam efficiency (Megeid et al., 2016).

In the studies examining seam performance about seam slippage, Özdemir and Yavuzkasap (2012) investigated the impact of yarn and fabric properties on seam slippage of double woven upholstery fabrics. They stated that seam slippage strength has increased as the weft density increased and sateen number of face weave decreased. In another study, Jankoska and Demboski (2017) examined the effect of weft density, weft yarn count and waterproof and oilproof finishing on the seam slippage. They found out that the increasing weft density had a positive effect on seam slippage property while waterproof and oilproof finish treatments affected negatively. Kalaoğlu and Meriç (2005) examined seam slippage of lining fabrics and they stated that weft density was the most important factor affecting seam slippage in lining fabrics and filament yarns, due to their smooth surface, caused more slippage than texturised yarns.

In studies about seam pucker; Cheng and Poon (2002) analysed seam strength, seam puckering and seam slippage of different woven fabric structures and they reported that plain weave fabric had higher seam strength and greater seam puckering than twill weave and as fabric weight and thickness increased, seam strength increased and seam puckering decreased. They also reported that the effect of weft and warp direction on seam strength varied according to the weave structure and as far as seam puckering is concerned, the seam

running parallel to the weft direction was less likely to exhibit for all fabric structures. In another study, Sharma et al. (2019) investigated seam puckering, seam stiffness, and seam thickness using eco-friendly silk and traditional silk yarns. They stated that blended fabrics made from eco-friendly silk and cotton were compatible with blended fabrics made from traditional silk and cotton yarns in terms of sewability parameters and could be preferred in clothing and textiles.

In studies on sewability; Yıldız et al. (2011) analyzed the sewability of four woven interlinings and three woven fabrics of different weights. The findings regarding penetration force, fabric unit weight, and fabric thickness showed that sewability resistance increased as the weight and thickness of fabrics levels increased. In another study examining sewability, Bakıcı and Kadem (2015) investigated the impact of 100% cotton woven fabrics with different weaving structures (twill, panama, plain) on fabric sewability. This study demonstrated fabric weave structure and weft density were parameters that affect fabric sewability. The best sewability was achieved with panama weaving fabrics the lowest weft density. There are also studies examining seam performance about seam strength and efficiency, seam slippage, seam pucker of cotton and polyester woven fabrics (Sülar et al., 2015), the effect of blend composition on suiting fabrics seam characteristics (Choudhary and Goel, 2013), seam performance of PET/Nylon-elastane woven fabrics (Gürarda, 2008), seam strength, seam slippage and seam efficiency of fabrics with different construction (Islam et al., 2019b) and the results of all these studies show that fabric construction or fabric structural properties has an effect on seam performance. Looking at the studies conducted specifically on denim fabric; it has been seen that; denim fabric mass and fabric raw material has an effect on seam efficiency property (Malek et al., 2017), sewing needle penetration forces are affected by the weft count and weft density

of fabric (Bakıcı and Kadem, 2018), the seam efficiency is increases with Lycra percentage (Padhye and Nayak, 2010).

Studies on the effects of dyeing and finishing processes on seam performance are available in the literature. When looking at the studies on this subject; Şevkan Macit (2024) analysed seam performance of dyed and finished polyester/viscose fabrics with different seam parameters. The author stated that the effects of bleaching, dyeing, finishing, laundering process and also seam parameters were effective on seam strength and seam efficiency. In another study, Şevkan Macit (2025) examined the influence of dyeing and finishing processes on seam efficiency of cotton fabrics and reported that the processes were related to seam efficiency. Köstem (2005) studied seam performance of anti-creasing finished woven fabrics and reported that finishing treatments were effective on seam performance properties. Farhana et al. (2015b) compared dyed and un-dyed gabardine apparels in terms of seam performance with different seam types. The authors concluded that dyeing process affects seam strength and the values of dyed garments had lower values compared to others. Kutgi and Zervent Ünal (2019) evaluated the effect of unbleached finish process on fabric performance by using bleached and unbleached cotton fabrics of the same construction. The researchers aimed to evaluate the applicability of pre-treatment stages without the bleaching process of cotton fabrics. They stated in terms of seam performance that the results of seam slippage were close to each other and at the desired level depending on the place of use. Kordoghli et al. (2009) investigated the effect of finishing process on seam performance. The authors revealed out that the increase of the stitch density increased the breaking resistance of seam and also they reported that there was an inversely proportional relationship between frequency of treatments and the seam resistance. Mukhopadhyay et al. (2004) investigated the effect of laundering on seam

properties with different parameters. They stated that the impact of coarser yarn was higher on seam properties of Polyester/Cotton blend fabric than cotton fabric. Elghandour et al. (2022) analysed seam properties of silk garments dyed with natural dyes by the parameters stitch density and dyeing time. The results demonstrated that seam stiffness was improved by reducing dyeing time and stitch density and higher stitch density was better for seam strength and seam elongation. They also pointed out recommended condition at dyeing time and stitch density to improve seam stiffness, seam slippage, seam strength and seam efficiency. Badr (2018) researched performance of knitted fabrics finished with different silicone softeners and the author stated about the sewability property of these fabrics that regarding the relationship between silicone type and stitch hole density, it was noted that fabric without micro silicone had the greatest seam hole value (lower sewability), while semi-micro silicone had the least seam hole value (higher sewability). Bakıcı (2019) aimed to improve the sewability property of polyester fabric by using sewing facilitating chemicals at different concentrations added to the dyebath. The researcher found out that as the concentration of chemicals added to the dyebath increased, the needle penetration forces in both directions decreased, thus improving the sewability of fabric. There are also studies examining the influence of different treatments on seam performance, especially on denim fabrics (Hafez and Saad, 2015; Rahman, 2011; Küçük, 2020; Bakıcı, 2017; Sarkar and Khalil, 2014).

3.3. Other Factors Affecting Seam Performance

In addition to factors related to fabric and sewing properties, factors such as machine, personal, environmental factors and noise levels can also affect seam performance (Yıldız and Pamuk, 2021). These factors should also be considered when evaluating seam performance.

4. CONCLUSION

Given the critical importance of seam performance for garment quality, various choices can be made to improve seam performance. When making these choices to optimize seam performance, it's important to consider fabric properties and sewing properties together and make choices by evaluating these factors. In this chapter, seam performance properties, sewing and fabric properties affecting seam performance, and previous studies on seam performance are examined.

To sum up previous studies; sewing properties such as seam type, stitch type, stitch density, seam direction, sewing thread type and count, needle size, sewing thread tension are effective on seam performance. On the other hand, fabric properties such as weave design, fabric weight, fabric thickness, yarn count and weft density of fabric, dye and finishing treatments, chemicals used and concentration have effect on seam performance. These results show that many factors should be taken into consideration to improve seam performance.

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ANTIMICROBIAL FUNCTIONALIZATION STRATEGIES IN THE CARPET INDUSTRY: EXISTING METHODS AND FUTURE PERSPECTIVES

Sevcan ÜSTÜN¹

1. INTRODUCTION

Historically, carpet making has reflected not only the creation of a textile surface but also a journey of history, culture, and art woven with knots. This process, extending from nomadic tents to palace corridors, has been one of the most concrete documents of humanity's transition to settled life and its search for aesthetics. They are initially produced to provide protection against the cold, these coarse woven fabrics have gradually transformed into a huge industry reflecting the beliefs, stories, and wealth of societies. A carpet is defined as a thick, short-pile, plain or patterned rug woven using textile material and generally used as a floor covering (GAHİB, 2022).

Carpet weaving started in the region inhabited by Turks in Central Asia, continued its development in Anatolia through migrations, gained great importance with its transport to Europe via the Silk Road, and spread as a luxury consumer product in Europe at the end of the 14th century (Çinko., 2018). At the beginning of the 16th century, Bergama and Menemen became important carpet centers, and after the middle of the 16th century, Uşak and its surroundings became important carpet centers. Figure 1. shows some types of carpets (Demiraslan, 2020). Until

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the 19th century, carpet weaving in Uşak and its surroundings continued, preserving its traditional characteristics (Tezcan, 2023).



Pazırık Carpet (a)
(Demiraslan, 2020)

Hereke Carpet (b)
(Demiraslan, 2020)

Uşak Carpet (c)
(Ürer, 2005)

Figure 1. Hand-woven carpet varieties (a, b, c)

Hereke carpets, in particular, with their use of silk and fine craftsmanship, became indispensable in European palaces. Until the 19th century, the sector relied entirely on hand labor, but it underwent a major transformation with the Industrial Revolution. In 1839, Erastus Bigelow reshaped the sector by inventing the carpet loom for weaving and opened the doors to mass production (URL1). During this period, carpets ceased to be a luxury consumer item and began to enter the homes of the middle class. While hand carpet weaving remained an "art," machine carpet weaving became a huge "industry" branch. With the transition to settled life, carpets became an indispensable part of palaces and places of worship, but because the concept of hygiene had not developed, the fact that dust and microorganisms formed an ecosystem went unnoticed. This hygienic problem began with the development of the modern chemical industry, and the process of modifying the yarns used started, which created a turning point in carpet weaving.

The protective effect of lanolin, a substance naturally found in traditional wool carpets, has been replaced by silver ion technologies and nano-coatings developed in laboratory settings. This technological development process has enabled the creation of surfaces in the carpet's weave that prevent bacterial growth and minimize mold and mildew formation. Modern carpets, especially those designed for hospitals, children's rooms, and urban areas, are no longer just decorative elements; they function as active hygiene barriers. Today, antibacterial carpets offer a permanent protective shield that doesn't disappear with washing, thanks to active components added during the yarn production process. Humanity has gone through countless stages to reach this point, from coarse animal hides to silk weaves, from hand looms to AI-powered factories. The latest stage is the concept of "smart carpets," opening up discussions about surfaces that can clean themselves or purify the air. This evolution of carpets actually reflects humanity's desire to control nature and make its living space more sterile. This story, which began with knots, has evolved into a high-tech defense line that fights microorganisms at a microscopic level. As a result, that coarse weave that only kept our feet warm in prehistoric times now holds its place in our homes as a modern engineering marvel equipped with biotechnological capabilities.

With the Industrial Revolution, when traditional weaving looms were replaced by massive steam engines, production speed increased, on the other hand the inherent problem of carpets becoming dirty and harboring bacteria still kept its significance. The discovery of synthetic fibers in the mid-20th century increased the durability of carpets, but brought with it new problems such as static electricity and allergen accumulation. Carpet making has become a concept that combines engineering and aesthetics, starting from humanity's most basic need for shelter and extending to today's high-tech laboratories.

Today, the carpet industry is shaped by digital printing techniques, smart yarn technologies and sustainability-focused production. The world carpet market is not only an aesthetic choice but also an integral part of the construction and decoration industry. While significant increases have been seen in world carpet exports in the last 15 years, a process of intense competition has also been experienced (Demiraslan, 2020). Global carpet and rug production reached a size of \$50 billion in 2023. It is projected that global production will grow at an average annual rate of 4.2% until 2032, increasing the market volume to \$75 billion. World carpet exports amounted to \$17.2 billion in 2023; our country is the second largest exporter after China with a 16% share of the world market (URL2). In 2025, \$2,838,515,000 in revenue was obtained from the export of 570,827,000 square meters of carpets (URL3). Figure 2. shows Türkiye's carpet and rug import and export revenue between 2020 and 2024. Our country, which is one of the world's largest producers and exporters of carpets and rugs, is projected to reach a size of \$2.2 billion in this sector in 2029 (URL2).



a) Türkiye Imports

b) Türkiye Exports

Figure 2. Türkiye's Carpet and Rug Import (a) and Export (b) Revenue Between 2020-2024 (URL2).

Turkey dominates approximately 26% to 30% of the world market, particularly in the machine-made carpet category. Designing user-friendly products in this carpet industry, with such a huge market, will ensure continued market share in the global market in the future. Antimicrobial carpets have evolved from being merely a decorative item to holding a critical market

share at the intersection of health and technology. Increased consumer awareness of hygiene standards in living spaces is increasing the importance of antimicrobial carpets. These carpets improve air quality and minimize respiratory problems by preventing dust mites and microorganisms dispersing into the air. For hospitals, nurseries, and hotels, which require high levels of sterilization, antimicrobial choices are no longer a preference but a necessity. Silver ions or nanotechnological components integrated into the yarn weave prevent bacterial growth, thus preventing unpleasant odors that develop in carpets over time.

For world-leading manufacturers like those in Turkey, offering antimicrobial properties provides a high value-added product advantage over competitors in the global market. In next-generation production, a balance between environmentally friendly recycled materials and antimicrobial protection will be achieved, establishing a "healthy and eco-friendly" product model. Unlike traditional carpets, the protective properties in models produced with nanotechnology do not easily disappear with washing; they remain active throughout the product's lifespan. Antimicrobial technology combined with an anti-allergic structure has made carpet use safe again for millions of consumers sensitive to house dust. With the widespread adoption of smart home systems, "active surface" carpets that can report microbial load on their surface or purify the air indicate the future direction of the market.

2. ANTIMICROBIAL FUNCTIONALIZATION IN THE CARPET INDUSTRY

The textile industry is evolving into a new era where user health and environmental sustainability parameters are prioritized, beyond aesthetic values. Carpets, an indispensable element of interior spaces, trap dust, moisture, and organic

residues due to their complex morphological structures and high pile surface areas. The proliferation of microorganisms on textiles during use and storage negatively affects the textile product and causes health problems (Dastjerdi et al., 2008). In addition, staining, discoloration, deterioration of strength, and other physical and chemical properties are just a few of the undesirable effects (Alagirusamy et al., 2010). These effects can be explained as follows: carpets, which trap waste, create a suitable ecosystem for the growth of microorganisms. These microorganisms, which develop here, lead to the formation of unwanted odors through volatile organic compounds, aesthetic deformations through the production of permanent pigments, and deterioration in the physical appearance of the material. Especially in natural polymer-based (cotton and wool) products, significant losses occur in functional parameters such as elasticity, strength, and feel as a result of the biodegradation process. Some fungal and bacterial species use textile finishing chemicals as a food source, disrupting the structural integrity of the product and shortening its service life (Orhan, 2007). As a result, fiber degradation, persistent stains, allergen formation and pathogen spread occur.

Today, functionalization strategies focus not only on biocide effects but also on systems that are sensitive to human health and have high wash resistance. This has led the carpet industry towards advanced antimicrobial solutions. The adhesion mechanisms of antibacterial agents to the three most commonly used fiber types in the carpet industry—polypropylene, acrylic, and wool—differ. Polypropylene, by its nature, is a non-polar and hydrophobic fiber. This property makes it difficult for finishing processes (apres) to adhere to the fiber surface. Because chemical bonding is difficult, inorganic additives are incorporated into the polymer matrix during melt-spinning. The antibacterial agent is mechanically trapped within the fiber. With fiber abrasion, a microscopic diffusion occurs towards the surface. Acrylic fibers

generally contain negatively charged (anionic) groups. This allows for strong bonding with positively charged (cationic) antibacterial agents. Quaternary ammonium compounds (QACs), or silver ions, with a cationic structure, bind to sulfonate or carboxylate groups in acrylic fibers via electrostatic attraction. This ionic bond provides higher wash fastness compared to physical adsorption. However, disruption of the charge balance on the fiber surface can also affect the static electricity properties of the carpet. Wool fiber, on the other hand, is a complex, amphoteric (capable of carrying both positive and negative charges) protein fiber composed of amino acids. The porous structure of wool fiber and the sulfur bridges (cystine bonds) within it can bind metal ions through chelation. Chitosan, a natural polymer, forms hydrogen bonds and covalent interactions with protein groups in wool under acidic conditions. Wool's high moisture absorption capacity facilitates the penetration of the antibacterial agent to the core (cortex) of the fiber.

3. METHODS OF ACHIEVING ANTIBACTERIAL PROPERTIES

To impart antibacterial properties to carpets, the most commonly used methods include antibacterial agents, polymeric matrix modification (masterbatch), sol-gel, coating technologies, and nanotechnology techniques.

3.1. Antibacterial Agents

Current antibacterial agents used in carpet production are examined within the scope of metal-based nanoparticles, quaternary ammonium compounds, and sustainability-focused natural plant extracts. Masterbatch additives, spray coating, and dipping methods, which are methods of integrating these agents into the fiber structure, can be compared in terms of efficacy and wash resistance. Figure 3. shows a textile product impregnated

with antimicrobial compounds. Antimicrobial agents kill microorganisms or cause cell wall damage by interfering with the necessary mechanism of the microbial cell (Çukul, 2013).

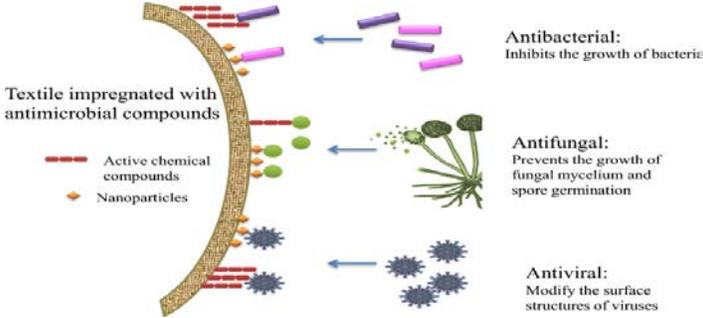


Figure 3. Textile impregnated with antimicrobial compounds(Gulati et al., 2022)

Metal-based nanoparticles, particularly silver and zinc oxide nanoparticles, show significant potential as antibacterial agents due to their broad-spectrum efficacy against both Gram-positive and Gram-negative bacteria. Cadmium, silver, copper, and mercury are very good antibacterial metals. The oxidation states of silver Ag^0 , Ag^+ , Ag^{2+} , and Ag^{3+} have long been considered to have inhibitory effects on many bacteria and fungi (Çukul, 2013). Zinc pyrithione is very potent not only against bacteria but also against mold and fungi that cause odors in carpets. Quaternary ammonium compounds follow a mechanical killing method. They break down the cell membrane of the microorganism and prevent bacteria from developing resistance to this method. Since synthetic agents, such as fourth-order ammonium compounds, are cationic surfactants that effectively target bacteria, fungi, and some viruses, they are frequently used as antimicrobial agents in textiles. To disrupt vital processes and kill microorganisms, their antibacterial effects involve electrostatic interactions between the positively charged nitrogen atom and the negatively charged microbial cell membrane (Ghosh et al., 2025). It measures the long-term protection of triclosan-

based and environmentally friendly passivation layers against *E. coli* and *S. aureus* and the resistance of these coatings to cleaning chemicals (Chen et al., 2024). It is a natural polymer obtained from shrimp and crab shells. High-end carpet brands that release "Organic" and "Vegan" collections use this biological agent as a marketing trump card.

Chitosan, plant extracts, essential oils, and natural dyes are among the most common antibacterial agents used to impart antibacterial properties. Chitosan is a natural antimicrobial agent derived from chitin. Chitosan has a wide range of uses due to its biodegradability, biocompatibility, antimicrobial activity, non-toxicity, and wound healing properties. Conventional fibers coated with chitosan are considered a more realistic option as they do not provoke an immunological response. Fibers made from chitosan are currently available on the market (Maurya et al., 2025).

Research shows that releasing antibacterial substances into the soil, highlighting the dual role of plant-based biomaterials as both coloring and antimicrobial agents, degrades soil health by destroying or inhibiting the activity of beneficial soil microorganisms (16). Synthetic antimicrobial agents, traditionally used in the carpet industry to inhibit microbial growth, although highly effective, have begun to be questioned due to cytotoxicity risks, environmental leaching problems, and the resistance that microorganisms develop against these chemicals. At this point, the sustainability-oriented "Green Textile" vision has brought to the agenda the reintegration of natural dyes, which have a history of thousands of years, into modern textile technologies (Orasugh et al., 2025).

Natural dyes are rich in flavonoids and tannins, which plants (roots, leaves, fruit peels) synthesize to protect themselves against pathogens. However, due to some technical and

sustainability issues involved in the production and application of these dyes, such as their lack of availability in standard ready-to-use forms, their unsuitability for machine use, and limited and unrepeatable tones, the total share of natural dyes in the textile sector is approximately 1%. Natural dyes are sustainable because they are renewable and biodegradable, but they cannot meet the large demand of the textile sector due to the prioritization of land use for food and feed purposes (Saxena et al., 2014). But the total share of natural dyes in the textile sector is approximately only 1 % due to certain technical and sustainability issues involved in the production and application of these dyes such as nonavailability in ready-to-use standard form, unsuitability for machine use, and limited and nonreproducible shades. Natural dyes per se are sustainable as they are renewable and biodegradable but they cannot fulfill the huge demand from the textile sector in view of the preferential use of land for food and feed purposes

Wool, being a protein fiber, can be a suitable environment for various bacteria and molds. The biodegradation of woolen products produces amino acids that can easily enter into microbial cells and be nutrient sources for microorganisms. In addition to these nutrients, the high moisture content and high storage temperature of wool are ideal conditions for the growth of fungi and bacteria. Also, environmental conditions such as humidity, temperature, pH, and light are important factors for the propagation of these organisms (Khosravi et al., 2024). When bioactive components are fixed to wool carpet yarns, they not only impart color but also create a natural defense mechanism by disrupting the cell wall integrity of gram-positive and gram-negative bacteria. In particular, chelation bonds formed by metal ions used in the mordanting process with dye molecules both increase color fastness and synergistically support antibacterial efficiency through ionic interactions (Samanta et al., 2009).

Studies have shown that wool samples dyed with madder dye exhibit a reduction rate of over 90% against *Escherichia coli* and *Staphylococcus aureus* bacteria and *Candida albicans* and *Candida tropicalis* (Khan et al., 2012). Pomegranate peel extract creates an inhibition zone on *Escherichia coli*, a gram-negative bacterium, that can compete with synthetic agents (Chauhan et al., 2024). Pomegranate (*Punica granatum*) and most other natural dyes have been found to have strong antimicrobial properties due to their high tannin content. In addition, it has been determined that various plant-derived natural dyes rich in naphthoquinones, such as juglone from the leaves and fruit bark of the walnut tree (*Juglans regia* L.) and lawson from henna (*Lawsonia inermis* L.), have antibacterial and antifungal properties (Deveoğlu et al., 2011). The buckthorn, used for the golden yellow color in Anatolian carpets, is a rich source of flavonoids (quercetin, rhamnetin) (Genç et al., 2023). Flavonoids have the ability to inhibit bacterial DNA synthesis. By disrupting intracellular enzyme activities, they break the replication cycle of the bacteria. It has been determined that the use of neem, basil and aloe oil emulsion in the application of antimicrobial handwoven carpet coating shows superior antibacterial properties on both gram-negative and gram-positive bacteria (Yadav et al., 2023).

3.2. Polymeric Matrix Modification (Masterbatch)

If the carpet is made of polypropylene (PP) or polyester (PET), the antibacterial agent is added during the melt stage. Inorganic additives such as Ag and Zn, which provide homogeneous dispersion in the polymer matrix, are added. This method ensures that the agent is trapped inside the fiber, offering high wash fastness and long-term effectiveness. In the production of carpet fibers containing thermoplastic fibers such as polypropylene, polyamide, and polyester, the antimicrobial agent is added to the molten polymer before yarn spinning. This method ensures that the agent is homogeneously distributed throughout

the entire cross-section of the fiber. While the polypropylene or polyester yarn is still in liquid form (extrusion stage), antibacterial additives are trapped inside the polymer. Carpets produced with this method do not lose their properties when washed. This is because the protection is not on the surface of the carpet, but in its genetics. When the antimicrobial efficacy results were evaluated, it was determined that studies containing fibers with zinc oxide and silver nanoparticles exhibited the best antimicrobial efficacy against both Gram-positive and Gram-negative bacteria (Erem, 2012).

3.3. Sol-Gel and Coating Technologies

The sol-gel process involves dissolving various metal salts and metal alkoxide initiating agents in a solvent such as alcohol or water, hydrolyzing them under acid or base catalysis, and condensation after heat treatment. In recent years, sol-gel technology has been widely researched to impart multiple functional properties to textile materials. Sol-gel technology, a nanotechnological application, offers advantages such as high efficacy and durability, use of low concentrations of chemicals, application at low temperatures, imparting multiple functions to textile materials in a single step, environmentally friendly application, simple application, and applicability to textile plants without requiring special equipment (Camlibel et al., 2022). The sol-gel method used for surface modification allows antimicrobial agents to adhere to the fiber surface by covalent bonds by creating inorganic network structures. This method is a preferred alternative, especially due to the thermal sensitivity of natural fibers such as wool and silk. With the sol-gel method, a thin, transparent, and durable ceramic network structure is formed on the fiber surface. With this method, functional groups are bonded to the textile substrate by covalent bonds, and a controlled release mechanism is developed. It was observed that the odor release properties of the coated fabrics were more successful in weekly

subjective evaluations before, after washing and after the abrasion test, according to the sol-gel method and the conventional method (Camlıbel et al., 2022). Figure 4. illustrates the sol-gel method for functional coatings for textiles.



Figure 4. Functional coatings for textiles: Sol- gel (Ghosh et al., 2025)

The coating process begins with the preparation of a concentrated solution of the antimicrobial agent, which is then applied to the textile material using a padding machine. This machine passes the fabric through rollers immersed in the solution, ensuring even distribution and penetration of the antimicrobial agent into the fabric fibers.

Spray coating technique allows for the controlled and homogeneous application of antimicrobial agents even on complex textile structures or three-dimensional surfaces. Antimicrobial solutions containing active substances such as organic compounds are atomized into small droplets using special equipment and sprayed onto the fabric; this process is shown in the following example (Orasugh et al., 2025 farka bak iki Oragush var). Figure 5. shows the spraying method.

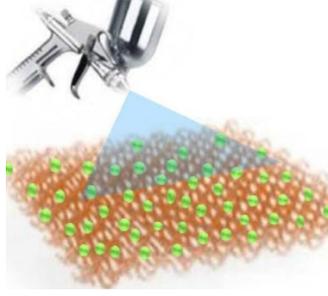


Figure 5. Spraying method (Dube et al., 2025)

Dip coating is a simple and effective technique used in the processing of antimicrobial textiles. This technique involves immersing the textile material in a solution containing an antimicrobial agent and allowing the material to absorb the solution homogeneously. It begins with the preparation of a concentrated antimicrobial solution that may contain antimicrobial agents. The textile is then immersed in this solution, allowing the antimicrobial agent to fully penetrate the fabric fibers. After a certain period, the fabric is removed from the solution and the excess liquid is removed. The textile is then subjected to a drying process to evaporate the remaining solvent and fix the antimicrobial agent to the fabric or within the fabric (Orasugh et al., 2025).

Screen printing is a technique used in the processing of antimicrobial textiles; in this technique, a stencil-based method is used to apply precise and patterned antimicrobial coatings to the fabric surface. This process involves creating a stencil on a fine-mesh screen. Figure 6. Schematic representation of screen printing.

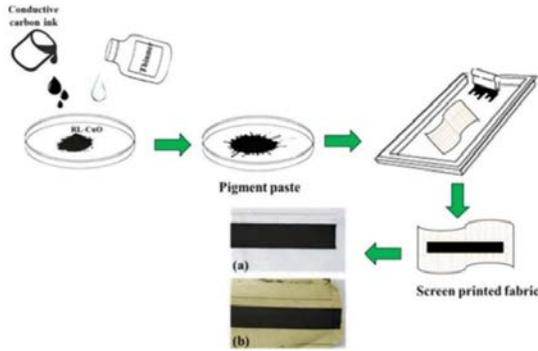


Figure 6. Schematic representation of screen printing (Orasugh et al., 2025)

Antimicrobial ink, which contains active substances such as antimicrobial compounds, is then pushed through the screen onto the fabric with the help of a squeegee. This allows the antimicrobial agent to be deposited in a controlled and patterned manner according to the design of the stencil (Orasugh et al., 2025).

3.4. Nanotechnology Methods

Biologically derived organic nanoparticles significantly enhance their antimicrobial performance thanks to their nanoscale size, large surface area, adjustable surface charges, and strong functionalization capacities. Obtained from renewable materials such as polysaccharides, proteins, and plant-based compounds, these nanoparticles offer a sustainable and environmentally friendly alternative to synthetic antimicrobial agents (Dube et al., 2025). Inorganic nanocomposites, especially silver-based coatings, used in controlling microbial contamination on carpet surfaces offer a sustainable solution. However, the trend towards natural and bio-based agents has accelerated in line with the industry's goal of minimizing environmental impacts (Chauhan et al., 2025). Ag, Cu, ZnO and TiO₂ nanoparticles exhibit higher efficacy at lower concentrations than conventional agents thanks

to their high surface/volume ratios. In the studies conducted, the possibilities of using metal and metallized conductive filaments in carpets and the properties they may impart to carpets have been investigated. It has been observed that they impart antibacterial, antifungal, antistatic and electromagnetic shielding properties to carpets (Özkan et al., 2016). Figure 7. shows a carpet treated with nanotechnology.



Figure 7. Nanotechnology carpet (URL4)

There are studies showing that the incorporation of titanium dioxide and nanoparticles into textiles enhances their antibacterial properties and achieves self-cleaning functions (Wang et al., 2010). Furthermore, there are studies that synthesize highly transparent self-cleaning films based on TiO₂ nanoparticles and impart advanced photocatalytic properties. Self-cleaning polymeric fibers are produced by depositing ZnO nanoparticles onto wool and polyacrylonitrile (PAN) fibers using the sol-gel method (Moafi et al., 2011). Innovative nanoparticles have shown great potential in improving various functional properties on textile surfaces such as color, antibacterial, hydrophilic, self-cleaning, ultraviolet (UV) protection and flame retardant properties (Doruk et al., 2024).

4. CHARACTERIZATION TECHNIQUES

Although achieving antimicrobial properties on textiles may seem easy, it requires the complete formulation of the

antimicrobial substance, its application to textiles with the determined formulation, the textile's improved antimicrobial properties, proof of safety, and finally, registration with the appropriate authorities (Orhan, 2007).

Carpets harbor pathogenic bacteria such as *Staphylococcus aureus* and *Escherichia coli*, as well as various mold fungi. The inability of traditional cleaning methods to completely eliminate the microbial load in the fiber depths has made antibacterial finishing treatments (applied during or after fiber production) necessary. For a carpet to be classified as "antibacterial," it must pass internationally accredited tests. The most commonly used standards are:

AATCC 174: 2022 - Test method for antimicrobial activity of new carpets evaluates the antimicrobial efficacy of new carpet materials, focusing on both antibacterial and antifungal properties. Determine the efficacy of antimicrobial agents incorporated into or applied onto new carpets. Evaluate a carpet's resistance to microbial growth. Compare the performance of antimicrobial-treated carpets to untreated ones (URL5). Provides both qualitative and quantitative assessments of antibacterial and antifungal properties Demonstrates adherence to industry standards, particularly important for manufacturers exporting carpets to regulated markets. (AATCC 174)

ASTM E2149-20 - Standard test method for determining the antimicrobial activity of antimicrobial agents under dynamic contact conditions. This standard test method measures the antimicrobial activity of treated materials using the dynamic liquid contact method .This test method may not be appropriate for all types of antimicrobial-treated articles or antimicrobial agents (ASTM E2149-20).

AATCC 100 - Antibacterial testing of fabrics AATCC 100 test method is performed to determine the efficacy of

antibacterial finishes applied . This American Association of Textile Chemists and Colorists (AATCC) method is used to evaluate the antimicrobial effectiveness of textile materials treated with antimicrobial agents. AATCC Test Method 100 is a quantitative assessment of how well a textile material finish is able to stand up to antibacterial activity in accordance with its intended use. It looks at both bacteriostatic (bacteria stopping) and bactericidal (bacteria killing) activity, offering detailed measurements that allow for continuity and replicable results. Standard microorganisms tested are Staphylococcus aureus and Klebsiella pneumoniae and allows other microorganisms depending on the intended use of the test sample (AATCC 100).

ISO 20743:2013 - specifies quantitative test methods to determine the antibacterial activity of all antibacterial textile products including nonwovens. It involves inoculating the textile with a standardized suspension of bacteria and assessing the reduction in bacterial count over time. ISO 20743:2013 is applicable to all textile products, including cloth, wadding, thread and material for clothing, bedclothes, home furnishings and miscellaneous goods, regardless of the type of antibacterial agent used or the method of application (ISO 20743:2013).

FT-IR (Fourier Transform Infrared Spectroscopy) is used to verify the chemical bonds of the agent on the fiber. SEM-EDX (Scanning Electron Microscopy) is used to image the surface distribution and elemental composition of nanoparticles.

These test standards establish a framework for assessing the antimicrobial efficacy of textiles under regulated circumstances, guaranteeing that the results are reproducible and similar across laboratories and products. The choice of the test procedure may depend on the particular purpose and the specific kind of microorganism being targeted (Orasugh et al., 2025).

5. FUTURE PERSPECTIVES

In the carpet industry, antibacterial applications not only ensure hygiene but also prevent unpleasant odors caused by microbial activity. Future research should focus on more clearly defining the biosafety limits of nanotechnology applications on human health in a more clarifying manner.

Future carpet technologies should aim to develop multifunctional surfaces that are not only antibacterial but also antistatic, odor-removing, and self-cleaning (photocatalytic). The future should be based on the principles of "green chemistry." Therefore, the use of biodegradable agents such as chitosan, sericin, and plant-based polyphenols has begun to replace synthetic biocides. Furthermore, stimulus-responsive systems developed within the scope of "smart textiles" minimize environmental pollution by releasing active substances only when humidity or microbial activity increases in the environment. Thanks to these systems, smart release mechanisms that are activated only when bacteria are observed will open a new chapter in textile literature.

Studies should gain more interest on "self-disinfecting" systems that break down bacteria by producing free radicals under indoor light, by integrating light-sensitive nanoparticles into carpet fibers.

Chemical and nanotechnological approaches used in the functionalization of synthetic and natural carpet fibers, their mechanisms of action, and environmental sustainability parameters should be investigated from a deeper aspect. In terms of environmental sustainability, limiting carbon emissions and raising awareness about climate change are among the main transformative factors in the global market. Therefore, industry actors should increasingly turn to sustainable, eco-friendly

carpets to minimize their negative impact on the environment (URL3).

Chemicals used in textile products pose risks in terms of environmental and legal obligations. Mismanaged chemical use may cause negative effects on both the environment and worker health. As a result, there is an increasing trend towards carpets with low carbon footprints. This trend may create a risk of market loss for businesses that do not adopt a sustainable product design and production approach. In addition, by using technologies that increase energy efficiency in production processes, reducing the carbon footprint, and complying with global customer expectations through environmental labeling and product certification practices, the trend towards environmentally friendly and harmless "Green Textile" solutions from chemical-based methods will ensure that market share will gradually increase (URL6).

Among the most common problems encountered in production are difficulties in accessing affordable, high-quality and sufficient raw materials, high input costs, the need for qualified labor, inadequacy in R&D and innovation activities, branding, marketing and financing problems, and lack of databases (Binboga et al., 2024). State-supported efforts and R&D activities should be increased to address these problems.

6. CONCLUSION

In the carpet industry, antibacterial functionalization has become not only a value-added feature but also a necessity in terms of public health and product sustainability. Based on the methods examined, the following key conclusions have been reached:

In contrast to the cytotoxicity and environmental leaching risks caused by synthetic antibacterial agents (silver nanoparticles, quaternary ammonium compounds, etc.), the biodegradable nature and human-health-friendly characteristics of natural dyes have proven them to be the most suitable alternative for "Green Textiles" and "Sustainable Home Textiles" concepts.

While masterbatch applications offer a permanent solution in non-polar fibers such as polypropylene, ionic and covalent bonding mechanisms have been found to be more effective in terms of wash resistance in fibers containing polar groups such as acrylic and wool. Solutions must be found to improve wash resistance in carpets that have been cleaned repeatedly, as their antibacterial properties are lost. While nano-silver and nano-zinc oxide applications provide the broadest spectrum of efficacy, the leaching of these particles into the environment over time and their ecotoxicological effects are still a subject of debate. Future studies are expected to focus on stronger anchoring of these agents to the fiber matrix.

The replacement of synthetic quaternary ammonium compounds with biodegradable chitosan, alginate, and microencapsulated essential oils have been an inevitable trend. However, improving the process stability (such as high-temperature resistance) of these natural polymers is a critical area of R&D. Standard color fastness and color retention issues, the biggest obstacles to the industrial-scale use of natural dyes, can be overcome with modern extraction methods and biotechnological modifications.

Photocatalytic carpets, currently in the R&D phase and being tested by some global brands, exist. When these carpets interact with light, they can oxidize and break down bacteria on their surface and airborne pollutants. These studies should be

compatibly integrated through novel and promising ecological methods.

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**TEKSTİL BİLİMLERİ VE MÜHENDİSLİĞİ ALANINDA
BİLİMSEL ARAŞTIRMALAR**

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