ACADEMIC DISCUSSIONS IN THE FIELD OF TEXTILE SCIENCE AND ENGINEERING

Editor: Assist. Prof. Dr. Hüsnü AYDEMİR

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yayınları

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Dr.Öğr.Üyesi Hüsnü AYDEMİR

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İÇİNDEKİLER

TEKSTİLDE DİJİTALLEŞME VE DİJİTAL ÜRÜN PASAPORTU

Gül ÖZKAN[1]

1. GİRİŞ

Tekstil ve hazır giyim sektörü, küresel ölçekte hem ekonomik hacmi hem de çevresel ve sosyal etkileri bakımından en kritik endüstriler arasındadır. Kaynakların yoğun kullanımı, karmaşık tedarik zincirleri, hızlı tüketim döngüleri ve yüksek atık üretimleri nedeniyle sektör, sürdürülebilirlik ve şeffaflık tartışmalarının merkezinde durumundadır (Niinimäki & ark., 2020). Dijitalleşme bu kapsamda, üretim verimliliğini artırmaya yönelik bir araç olmanın ötesinde; çevresel sorumluluk, etik üretim ve tüketici bilgilendirmesi gibi çok boyutlu hedeflerin gerçekleştirilmesinde stratejik bir faktör hâline gelmiştir.

Tekstil sektöründe dijitalleşme; nesnelerin interneti, büyük veri analizi, yapay zekâ, dijital ikiz, ürün yaşam döngüsü yönetimi ve izlenebilirlik sistemleri gibi teknolojilerin yaygınlaşmasıyla da hız kazanmıştır (Petrillo & ark., 2024). Bu teknolojiler, ürünün hammaddeden son kullanıcıya kadar geçen tüm süreçlerin dijital olarak kayıt altına alınmasını mümkün hale getirerek, sektörün uzun süredir eleştirilen şeffaflık sorununa yapısal bir çözüm sunmaktadır.

Bu süreç, endüstri 4.0 ile başlamış ve günümüzde Avrupa Birliği başta olmak üzere birçok ülke ve kurum tarafından endüstri 5.0 yaklaşımı çerçevesinde de yeniden ele alınmaktadır. Endüstri 5.0; yalnızca otomasyon ve verimlilik merkezli bir

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sanayi anlayışını değil, insan merkezli, sürdürülebilir ve dayanıklı üretim sistemlerini temel almaktadır (European Commission, 2021). Tekstil sektörü gibi emek yoğun ve olumsuz çevresel etkileri yüksek bir endüstride, bu yaklaşım dijitalleşmenin yönünü belirleyen temel çerçeve hâline gelmiştir.

Endüstri 5.0 yaklaşımının tekstil sektöründeki en somut yansımalarından biri Dijital Ürün Pasaportu (DÜP) uygulamalarıdır. Dijital Ürün Pasaportu; bir tekstil ürününe ait hammadde içeriği, üretim süreci, çevresel etki göstergeleri, bakım talimatları ve geri dönüşüm bilgileri gibi verilerin dijital ortamda yapılandırılmış biçimde sunulmasını amaçlayan bir sistemdir (European Parliamentary Research Service [EPRS], 2024).

Dijital Ürün Pasaportu uygulamaları, tekstil sektöründe yalnızca düzenlemeler arası uyumunu sağlamakla kalmamakta; aynı zamanda tüketicilerin bilinçli tercih yapabilmesini, üreticilerin çevresel etkilerini ölçmesini ve geri dönüşüm süreçlerinin etkinliğini artırmasını da mümkün kılmaktadır (Pigosso & ark., 2022). Avrupa Birliği pazarına yüksek düzeyde bağımlı olan Türk tekstil sektörü, DÜP gibi dijital ve sürdürülebilirlik merkezli uygulamaları yalnızca rekabet avantajı için değil, aynı zamanda pazar erişimini sürdürebilmek için de gündemine almak ve uygulamaya geçirmek durumundadır (Aksoy & ark., 2023).

Bu çalışma, tekstil sektöründe dijitalleşme kavramını endüstri 5.0 kapsamında ele alarak, Dijital Ürün Pasaportu uygulamalarının teorik altyapısını ve pratikteki etkilerini incelemeyi amaçlamaktadır. Çalışma kapsamında, bazı Avrupa Birliği ülkeleri ve Türkiye ölçeğinde tekstil sektöründe dijitalleşme ve DÜP uygulama örnekleri değerlendirilmiştir. Bu yönüyle araştırma, hem akademik literatüre güncel bir katkı sunmayı hem de sektör paydaşları için yol gösterici bir kapsam oluşturmayı hedeflemektedir.

2. LİTERATÜR

2.1. Tekstilde Dijitalleşmenin Tanımı, Temel Bileşenleri ve Uygulama Alanları

Dijitalleşme; fiziksel süreçlerin bilgi ve iletişim teknolojileri ile dijital ortama aktarılması ve bu süreçlerin de veriye dayalı yönetilmesi anlamına gelmektedir (Pal & Jayarathne, 2022). Bu dönüşüm, üretimden tedarik zincirine, tasarımdan ürün yaşam döngüsü takibine kadar tüm faaliyet ve süreçlerin dijital teknolojiler aracılığıyla optimize edilmesi anlamına gelmektedir.

Dijitalleşme, tekstil sektörünü aşağıda sıralanmış alanlarda etkilemektedir:

1. Tasarım ve Ürün Geliştirme: CAD/CAM, 3D dijital tasarım ve sanal prototipleme teknikleri ile ürün geliştirme süreçleri kısalır ve olumsuz çevresel etkiler azalır (Glogar, 2025). Bu uygulamalar, tasarım inovasyonunu destekler böylece pazara çıkış süreleri kısalır.
2. Akıllı Üretim Süreçleri: Nesnelerin interneti (IoT), üretim makinelerinden sensörlere kadar fiziksel unsurların internet üzerinden birbirine bağlanarak bilgi alışverişi yapmasını sağlar. Bu sayede üretimdeki arıza tahmini, enerji verimliliği ve envanter optimizasyonu gibi süreçler dijital olarak yönetilir (Petrillo & ark., 2024). IoT, otomasyon ve veri analitiği gibi teknolojiler sayesinde üretim hatlarının esnekliğini,

kalite kontrolünü ve süreç verimliliği de artmaktadır (Petrillo, 2024).

3. Tedarik Zinciri Yönetimi: Tekstil sektöründe tedarik zinciri, çok aşamalı ve coğrafi olarak dağınık bir yapı sergilemektedir. Bu durum, izlenebilirlik ve şeffaflık açısından ciddi zorluklar doğurmaktadır (Bermeo-Giraldo & ark., 2023). Tüm verilerin standartlaştırılmış dijital formatta toplanmasını sağlamak bu soruna çözüm sunmaktadır. Kurumsal kaynak planlama (ERP) ve dijital izlenebilirlik araçları sayesinde tedarik zinciri daha açık, hızlı ve koordineli hale gelmektedir (Bermeo-Giraldo, 2025).
4. Tüketici ile Etkileşim: Ürün verileri, dijital kanallar üzerinden şeffaf şekilde tüketiciye sunulabilir (Glogar, 2025). Bunun için qr kod ya da dijital etiket uygulamaları kullanılır. Bu yeşil pazarlama ve bilinçli tüketim için de güçlü bir koldur.
5. Dijital İkiz (Digital Twin) Teknolojisi: Dijital ikizler, fiziksel süreçlerin sanal kopyalarıdır. Üretim sistemlerinde dijital ikiz kullanımı, makine performansını gerçek zamanlı olarak izlemeyi ve olası arızaları öngörmeyi sağlar (Özcan, 2025). Bu teknoloji ayrıca sürdürülebilirlik hedeflerine ulaşmak için enerji ve hammadde kullanım optimizasyonu sağlar.
6. Akıllı Tekstiller ve Sensör Entegrasyonu: Akıllı tekstiller, gömülü sensörler ve elektronik bileşenlerle donatılarak giyilebilir teknoloji, sağlık izleme ve performans analizleri gibi yeni alanlara açılmaktadır (Li & ark., 2024). Bu, tekstili yalnızca bir ürün değil veri üreten bir platform haline getirmektedir.

2.2. Dijital Ürün Pasaportu

Dijital Ürün Pasaportu, bir ürünün yaşam döngüsü boyunca üretilen teknik, çevresel ve tedarik zinciri verilerinin dijital ortamda yapılandırılmış biçimde saklandığı ve paylaşıldığı bir bilgi sistemi olarak da tanımlanabilmektedir (European Parliament Research Service, 2024; Pigosso & ark., 2022). Dijital Ürün Pasaportu, sadece bilgi depolamaya yönelik bir araç değil; ürün yaşam döngüsü boyunca üreticiler, tüketiciler ve geri dönüşüm faktörleri arasında şeffaf veri paylaşımını artırmayı amaçlayan dijital bir altyapı olarak değerlendirilmektedir (Pigosso & ark., 2022).

Böylece, tekstil ürünleri için izlenebilirlik, şeffaflık ve döngüsel ekonomi uygulamalarını desteklemek amacıyla kullanılan dijital ürün pasaportları sayesinde dijitalleşme ile tam dönüşüm de gerçekleşmiş olur.

DÜP uygulaması için tekstil firmalarının veri toplama sistemlerini, ERP/PIM altyapılarını ve paydaşlarla entegre ICT sistemlerini de kurması gereklidir. Her ürün için benzersiz bir dijital kimlik (örneğin QR kod, RFID) oluşturulur ve bu kimlik üzerinden dijital pasaporta erişim sağlanır (European Parliament Research Service, 2024).

Teknolojik entegrasyon, veri standardizasyonu ve tedarik zinciri paydaşlarının birlikte çalışması DÜP uygulamalarındaki en önemli zorluklar/sınırlılıklar arasındadır (Domskiene & Gaidule, 2024). Ayrıca farklı BT sistemleri arasında veri paylaşımı standartlarının oluşturulması gerekliliği de bulunmaktadır.

Avrupa Birliği'nde tekstil ürünleri için Dijital Ürün Pasaportu uygulamasının, sürdürülebilir ürünler için Eko-Tasarım Yönetmeliği kapsamında kademeli olarak zorunlu hâle getirilmesi planlanmaktadır. Bu çerçevede tekstil, dijital ürün pasaportu'nun öncelikli uygulanacağı sektörler arasında yer almaktadır (European Commission, 2022; European Parliament Research Service, 2024).

Endüstri 5.0 yaklaşımı, Endüstri 4.0'ın verimlilik ve otomasyon merkezli yapısını aşarak insan merkezlilik, sürdürülebilirlik ve dayanıklılık ilkelerini ön plana çıkarmaktadır (European Commission, 2021). Bu değişim, tekstil sektöründe dijitalleşme uygulamalarının yalnızca teknolojik değil; etik, çevresel ve toplumsal boyutlarıyla ele alınmasını zorunlu kılmaktadır. DÜP uygulamaları, endüstri 5.0'ın bu üç temel ilkesinin kesişim noktasında konumlanmaktadır.

Endüstri 5.0, dijital teknolojilerin insan emeğinin yerine konan değil, insanla birlikte çalışan sistemler olarak tasarlanmasını öngörmektedir (Breque & ark., 2021). Tekstil sektöründe bu yaklaşım; tasarımcı, üretici, tüketici ve geri dönüşüm faktörlerinin dijital sistemler aracılığıyla etkileşim halinde olduğu çok paydaşlı bir ekosistemi ifade edilmektedir. DÜP, bu ekosistemde bilgi paylaşımını mümkün kılan temel altyapılardan biridir.

DÜP, yalnızca bir izlenebilirlik, şeffaflık aracı değil; karar destek sistemi olarak da işlev görmektedir (Carvalho, 2023; Pigosso & ark., 2022). Ürün pasaportları sayesinde tasarımcılar malzeme seçimini, üreticiler çevresel etkiyi, tüketiciler ise satın alma kararlarını bilinçli biçimde şekillendirebilmektedir.

3. BULGULAR VE TARTIŞMA

Literatür taraması kapsamında incelenen çalışmalar, dijitalleşme uygulama alanları, dijital ürün pasaportu ile ve Endüstri 5.0 ile olan ilişkileri ve aynı zamanda teknolojik yaklaşımları şeklinde olmak üzere tablolar aracılığıyla karşılaştırmalı olarak değerlendirilmiştir.

Bulgular akademik literatürde raporlanan uygulamalarda, ürün yaşam döngüsüne ilişkin su, enerji ve kimyasal kullanımına dair çevresel performans göstergelerinin ölçülmesi ve raporlanması, sürdürülebilir ürün yönetiminin temel unsurlarındandır (Pigosso & ark., 2022). Bu veriler, yalnızca düzenlemelere uyum amacıyla değil, aynı zamanda kurumsal sürdürülebilirlik stratejilerinin şekillendirilmesinde de kullanılabilmektedir.

Endüstri 5.0 yaklaşımında tasarım süreci, teknik olduğu kadar etik bir süreç olarak da ele alınmaktadır. Dijital ürün pasaportları, tasarım aşamasında ürünün tüm yaşam döngüsünü görünür kılarak eko-tasarım ilkelerinin uygulanmasını kolaylaştırmaktadır (Mestre & Cooper, 2017). Eko – tasarım ilkesinde ürünün tüm yaşam döngüsünde oluşacak olumsuz çevresel etkilerin en aza indirgenmesi amaçlanmaktadır.

Örneğin, tasarımcılar DÜP verileri aracılığıyla malzemenin geri dönüştürülebilirliğini, karbon ayak izini ve önceki yaşam döngüsü performansını değerlendirebilmektedir. Bu yaklaşım, “üret–kullan–at” modelinden uzaklaşarak yeniden üret–yeniden kullan eksenli bir tekstil anlayışını desteklemektedir (Carvalho, 2023).

Üretim süreçlerinde DÜP, IoT ve siber fiziksel sistemlerle entegre çalışarak kalite yönetimi ve süreç kontrolü açısından önemli avantajlar sunmaktadır. Akademik çalışmalar, üretim parametrelerinin DÜP ile ilişkilendirilmesinin hata tespiti, geri çağırma süreçleri ve kalite belgelendirmesinde etkinliğinin arttırılmasına katkı sağlayabilmektedir (Petrillo & ark., 2024).

Bu kapsamda DÜP, Endüstri 5.0’ın dayanıklılık ilkesini destekleyen bir araç olarak değerlendirilmektedir. Tedarik kesintileri veya kalite sorunları gibi kriz durumlarında ürün ve süreç verilerine hızlı erişim sağlayabiliyor olmak işletmelerin uyum kapasitesini güçlendirmektedir.

Endüstri 5.0 yaklaşımının en belirgin farkı, tüketicinin pasif bir alıcı olmaktan çıkıp bilgiye erişebilen ve karar sürecine katılan bir faktör haline gelmesidir. DÜP uygulamaları, QR kod veya NFC etiketleri aracılığıyla tüketicilere ürünün çevresel ve sosyal etkilerine ait bilgilere erişimi kolaylaştırmaktadır (European Commission, 2022).

Araştırmalar, bu tür şeffaf bilgi sunumunun tüketici güvenini artırdığını ve sürdürülebilir ürünlere yönelik talebi desteklemektedir (Niinimäki & ark., 2020). Bu durum, DÜP'nin yalnızca teknik değil, davranışsal ve sosyolojik etkilerinden de söz edilebilecek olan dijital bir araç olduğunu göstermektedir.

Dijital Ürün Pasaportu'nun tekstil sektöründeki en güçlü katkılarından biri, ürün yaşam döngüsünün tamamlanmasına yönelik sağladığı altyapıdır. DÜP, ürünün kullanım sonrası aşamasında geri dönüşüm, yeniden kullanım veya yeniden üretim süreçlerine rehberlik eden kritik verileri içererek rehberlik edebilir (Pigosso & ark., 2022). Yaşam döngüsü temelli veri yönetimi yaklaşımı, endüstri 5.0'ın sürdürülebilirlik ilkesiyle ilişkilendirilebilir. Böylece tekstil atıklarının da azaltılmasına yönelik sistematik çözümler sunmaktadır (Mestre & Cooper, 2017).

Tablo 1. AB Üyesi Ülkeler İçin Dijital Ürün Pasaportu Uygulamalarına Yönelik Kavramsal ve Literatür Temelli Bir Karşılaştırma

No	Ülke / Bölge	Uygulama Alanı	Kullanılan Dijital Teknolojiler	DÜP Kapsamı	Endüstri 5.0 ile İlişkisi	Akademik Kaynak
1	İsveç	Moda Perakendesi	QR, GS1 standardı	Tedarik zinciri izlenebilirliği	İnsan merkezli bilgi erişimi	Carvalho (2023)
2	Hollanda	Döngüsel Tekstil Sistemleri	RFID, dijital kimlik, veri platformu	Geri dönüşüm ve yeniden kullanım verileri	Sürdürülebilirlik ve döngüsellik	Pigosso & ark. (2022)
3	Almanya	Teknik Tekstil	IoT, dijital ikiz	Üretim parametreleri, kalite verileri	Dayanıklılık	Petrillo & ark. (2024)
4	İtalya	Lüks Moda	QR/NFC, PLM sistemleri	Etik üretim, menşe bilgisi	İnsan merkezli değer üretimi	Glogar (2023)
5	Fransa	Tekstil Geri Dönüşümü	Döngüsel tasarım, veri tabanı	Elyaf bileşimi, ayrıştırma talimatı	Döngüsel ekonomi	Mestre & Cooper (2017)
6	Finlandiya	Akıllı Tekstil, Sürdürülebilirlik	Sensör entegrasyonu	Ürün performans ve kullanım verisi	İnsan-teknoloji iş birliği	Niinimäki & ark. (2020)
7	Danimarka	Sürdürülebilir Moda Tedarik Zinciri	QR, yaşam döngüsü analizi	Çevresel etki göstergeleri	Bilinçli tüketim	Carvalho (2023)
8	İspanya	Hızlı Moda Tedarik Zinciri	QR, ERP-DÜP entegrasyonu	Tedarik zinciri şeffaflığı	Etik üretim	Bermeo-Giraldo & ark. (2023)

Tablo 1'de verilen literatür örnekleri incelendiğinde, tekstil sektöründe dijital ürün pasaportu ile ilişkilendirilen dijitalleşme uygulamalarının farklı alt alanlarda çeşitlendiği görülmektedir. İncelenen çalışmalar, moda perakendesi, teknik tekstiller, geri dönüşüm süreçleri ve tedarik zinciri yönetimi gibi alanlarda DÜP kapsamına girebilecek veri türlerinin farklılaştığını ortaya koymaktadır. Bu bulgu, DÜP uygulamalarının sektörün ihtiyaçları doğrultusunda değişen bir yapıya sahip olduğunu göstermektedir.

Kullanılan dijital teknolojiler açısından incelendiğinde, QR kod ve GS1 standartlarının özellikle moda perakendesi ve tedarik zinciri uygulamalarında öne çıktığı görülmektedir. RFID, IoT ve dijital ikiz gibi daha ileri dijital teknolojilerin ise teknik tekstiller ve performans odaklı ürünlerde kullanıldığı belirlenmiştir.

DÜP kapsamı incelendiğinde, tedarik zinciri izlenebilirliği, hammadde bileşimi, üretim parametreleri ve çevresel etki göstergelerinin literatürde en sık vurgulanan başlıklar olduğu görülmektedir. Özellikle döngüsel tekstil ve geri dönüşüm odaklı çalışmalarda, elyaf bileşimi ve ayrıştırma bilgilerinin öne çıktığı görülmektedir.

Endüstri 5.0 ile ilişkilendirilen özellikleri değerlendirildiğinde, insan merkezli bilgi erişimi, sürdürülebilirlik, dayanıklılık ve bilinçli tüketim kavramlarının ön plana çıktığı görülmektedir. Tablo 1'den çıkarılabilecek sonuç; dijital ürün pasaportu uygulamalarının yalnızca teknik bir izleme aracı olmadığını; Endüstri 5.0 yaklaşımının öngördüğü insan merkezli, sürdürülebilir ve dayanıklı üretim sistemlerinin somut bir bileşeni olarak işlev gördüğüdür. Uygulama örnekleri, DÜP'nin tekstil sektöründe tasarımdan üretime, tüketici etkileşiminden geri dönüşüme kadar doğrudan ya da dolaylı olarak geniş bir etki alanına sahip olduğunu göstermektedir.

Tablo 2. Türkiye'de Gerçekleştirilen DÜP Uygulama Örnekleri

No	Türkiye'de Uygulama Alanı	Sektör	Kullanılan Dijital Teknolojiler	DÜP Kapsamı	Endüstri 5.0 ile İlişkisi	Akademik Kaynak
1	Hazır Giyim İhracatı	Büyük ölçekli konfeksiyon firmaları	QR kod, ERP, PLM	Ürün menşei, malzeme bilgisi, izlenebilirlik	İnsan merkezli şeffaflık	Atilgan & Çelik (2022)
2	Organik Pamuk Tekstili	Ege Bölgesi tekstil işletmeleri	Blockchain, QR	Elyaf kaynağı, sertifikasyon verisi	Sürdürülebilirlik	Köksal & ark. (2021)
3	Ev Tekstili	Denizli tekstil kümelenmesi	RFID, dijital etiketleme	Ürün yaşam döngüsü takibi	Dayanıklı üretim	Yıldız & Sezgin (2023)
4	Teknik Tekstil	TÜBİTAK destekli Ar-Ge projeleri	Dijital ikiz, veri platformları	Performans ve üretim verileri	İnsan makine iş birliği	Demir & ark. (2020)
5	Tekstil Geri Dönüşümü	Mekanik geri dönüşüm tesisleri	Dijital sınıflandırma sistemleri	Elyaf bileşimi bilgisi	Döngüsel ekonomi	Uçar & Becerir (2019)
6	Moda Tasarımı	Üniversite–sanayi iş birlikleri	Dijital ürün kimliği, CAD	Tasarım-üretim entegrasyonu	İnsan merkezli tasarım	Ertekin & Atik (2021)
7	Sürdürülebilir Tekstil Sertifikasyonu	Türk tekstil ihracatçıları	Dijital sertifika entegrasyonu	DÜP veri altyapısı	Regülasyon uyumu	Aksoy & ark. (2023)
8	Akıllı Tekstil Ürünleri	Ar-Ge merkezleri	IoT, sensörlü tekstiller	Kullanım ve performans verisi	İnsan merkezli inovasyon	Güneşoğlu & ark. (2020)

Tablo 2'de verilen bilgiler incelendiğinde, Türkiye merkezli uygulama örneklerinin, tekstil sektöründe dijitalleşme süreçlerinin farklı alt alanlarda ve kurumsal yapılarda çeşitlilik gösterdiğini ortaya koymaktadır. İncelenen çalışmalar, hazır giyim ihracatından organik pamuk üretimine, teknik tekstillerden geri dönüşüm süreçlerine kadar geniş bir uygulama yelpazesini kapsamaktadır. Bu durum, dijital teknolojilerin tekstil sektöründe tek bir üretim aşamasıyla sınırlı kalmadığını, tasarım, üretim, kullanım ve kullanım sonrası süreçleri içeren bütüncül bir yapıyı kapsadığını göstermektedir.

Kullanılan dijital teknolojiler açısından değerlendirildiğinde, QR kod, ERP ve PLM sistemlerinin özellikle büyük ölçekli konfeksiyon firmalarında ve ihracat odaklı yapılarda tercih edildiği görülmektedir. RFID ve dijital etiketleme uygulamalarının ev tekstili ve ürün yaşam döngüsü takibine yönelik çalışmalarda öne çıktığı; dijital ikiz ve veri platformlarının ise teknik tekstiller ve Ar-Ge temelli projelerde kullanıldığı belirlenmiştir. IoT sensörlü tekstillerin ise daha çok kullanım ve performans verilerinin izlenmesine odaklandığı anlaşılmaktadır.

DÜP kapsamı incelendiğinde, ürün menşei, hammadde bileşimi, sertifikasyon bilgileri ve yaşam döngüsü verilerinin literatürde öne çıkan başlıklar olduğu görülmektedir. Özellikle geri dönüşüm ve sürdürülebilir tekstil sertifikasyonu alanlarında, elyaf bileşimi bilgisinin kritik bir veri unsuru olarak ele alındığı dikkat çekmektedir. Endüstri 5.0 ile olan ilişkisi açısından incelendiğinde, insan merkezli şeffaflık, sürdürülebilirlik, dayanıklı üretim ve insan-makine iş birliği gibi kavramların öne çıktığı tespit edilmiştir. Bu bulgu, Türkiye'deki uygulamaların ağırlıklı olarak teknolojik dönüşümün sosyal ve çevresel boyutlarıyla ilişkilendirildiğini de göstermektedir.

Türkiye'de tekstil sektöründe Dijital Ürün Pasaportu kavramı henüz AB'deki gibi yasal zorunluluk düzeyine ulaşmamış olmasına rağmen, özellikle ihracat odaklı firmalarda ürün izlenebilirliği, dijital etiketleme ve yaşam döngüsü verilerinin toplanmasına yönelik uygulamaların fiilen hayata geçirildiği görülmektedir. Bu uygulamalar, Dijital Ürün Pasaportu'nun temel bileşenleri olan veri şeffaflığı, sürdürülebilirlik ve tüketici bilgilendirmesi açısından Endüstri 5.0 yaklaşımıyla da doğrudan ya da dolaylı olarak örtüşmektedir.

4. SONUÇ

Bu çalışma, tekstil sektöründe dijitalleşme kavramını, Endüstri 5.0 yaklaşımıyla ele alarak, dijital teknolojilerin yalnızca verimlilik değil; insan merkezlilik, sürdürülebilirlik ve dayanıklılık ekseninde yer aldığını ortaya koymaktadır. Dijital Ürün Pasaportu, bu dönüşümün en somut ve sistematik araçlarından biridir ve giderek artan bir öneme sahiptir.

Literatür incelemeleri, DÜP'nin tekstil ürünlerinde şeffaflığı artırmakla kalmayıp; tasarım, üretim, tedarik zinciri yönetimi ve tüketici etkileşimi süreçlerini bütüncül biçimde dönüştürdüğünü göstermektedir. Endüstri 5.0 kapsamında DÜP, teknolojik bir veri deposu olmanın ötesinde, etik üretim, bilinçli tüketim ve döngüsel ekonomi hedeflerini de destekleyen stratejik bir yapı olarak değerlendirilmelidir.

Dijitalleşme, moda sektöründe sürdürülebilir tasarım uygulamalarını kolaylaştırarak ve kaynak kullanımı optimize ederek, olumsuz çevresel etkilerin azaltılmasına katkı sağlayacağı belirtilmektedir (Varol & Atalay Onur, 2025). Örneğin, IoT tabanlı sistemler enerji ve su tüketimini gerçek zamanlı olarak izleyerek kaynak verimliliğini destekleyebilir (Glogar, 2025). Üretim kalitesinin artmasıyla birlikte, hata oranlarının da azalacağı öngörülmektedir (Çalış Duman, 2024).

DÜP uygulamalarının yaygınlaşabilmesi için veri standardizasyonu, dijital altyapı yatırımları ve paydaş iş birliği gibi konularda önemli adımlar atılması gerekmektedir. Bu zorlukların aşılması halinde tekstil sektöründe dijitalleşmenin çevresel ve toplumsal faydalarının belirgin biçimde artacağı düşünülmektedir.

Tekstilde dijitalleşme ve dijital ürün pasaportu uygulamaları, Endüstri 5.0'ın öngördüğü insan merkezli ve sürdürülebilir sanayi düşüncesinin hayata geçirilmesinde kilit bir noktadadır. Bu kapsamda DÜP, geleceğin tekstil endüstrisi için yalnızca bir düzenleyici değil, aynı zamanda stratejik öneme sahip bir dönüşüm aracı olacaktır.

Tekstilde dijitalleşme, sadece üretim süreçlerini dönüştürmekle de kalmaz; aynı zamanda sürdürülebilirlik, döngüsellik, kalite ve şeffaflık hedefleriyle sektörün rekabet edebilme gücünü de arttıracaktır.

Gelecek çalışmalarda, tekstil sektöründe yeşil dönüşüm uygulamaları kapsamında dijital ürün pasaportu incelenebilir. Sanayi/firma uygulama analizleri ile sektör bazlı sayısal veri değerlendirmeleri yapılarak literatüre katkılar sunulabilir. Dünya ve Türkiye örnekleri karşılaştırmalı olarak incelenebilir.

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NANOFIBER APPLICATIONS IN MEDICAL TEXTILES AND WOUND DRESSINGS

Sevcan ÜSTÜN[1]

Ayşe Ebru TAYYAR[2]

1. INTRODUCTION

Textile products, with their very wide range, have maintained their presence in many sectors for many years. Beyond classic textile products, the emergence of new application areas has resulted in the birth of the concept of technical textiles, and the growth rate of technical textile products in the market has increased. Technical textiles refer to textile products with special functionalities, different from conventional textile materials. These special functions enable technical textiles to be used in industrial, commercial, or private applications. Technical textiles generally include high-performance materials that are durable, have special coatings, or are designed to meet specific requirements. This offers numerous useful applications that vary across industries. Technical textiles are materials with technical and quality functions, possessing many high mechanical, thermal, and electrical properties.

Medical textiles are one of the fastest-growing sub-branches of technical textiles, directly in contact with human health. While traditional textile materials have historically been used for protection and absorbency, modern applications focus on

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biochemical interaction (Bartels, 2011). The wound healing process is a dynamic mechanism that begins with the disruption of tissue integrity and consists of complex biological stages. Textile structures used in this process should not only act as a barrier but also provide an environment that accelerates healing. Traditional cotton gauze is insufficient in modern medicine due to its disadvantages such as adhesion to the wound and inability to maintain moisture balance. New studies show that nanoparticles are embedded on the surface of cotton fabric to impart antibacterial, easy stain removal, and UV protection properties (Doruk et al., 2024). An ideal wound dressing should protect the wound from external contamination while allowing gas permeability. Maintaining moisture balance on the wound is vital for cell migration and proliferation. In recent years, polymer science and nanotechnology have enabled the creation of revolutionary solutions in wound care (Zhumagaziyeva, 2021). Nanofiber structures, with their high surface area and porous nature, are at the heart of these solutions. Structures that mimic the extracellular matrix in the human body have opened a new era in tissue engineering (Yang and Xu, 2023). Furthermore, the effects of nanofibers on wound healing rate and infection control are being demonstrated with scientific data. Technological advancements have paved the way for systems called smart wound dressings that can deliver drugs (Mele, 2016).

The medical textile market in Turkey and worldwide is increasing its added value day by day with these innovative products. The mechanical strength and biocompatibility of nanofibers are considered among the most critical parameters for clinical success (Can and Ersoy, 2014). Currently, the integration of smart textiles into wound monitoring processes is also attracting significant interest. This transformation has the potential to increase patient comfort while reducing the financial burden on healthcare systems.

With advancing technology, medical textiles are finding applications in every stage of the healthcare sector. For example, they are used in many different forms such as sutures, surgical gowns, wound dressings, bandages, and vascular grafts. In the modern era, with the impact of epidemic diseases, the medical textile sector has become an important and rapidly developing branch of the textile industry. Medical textiles are textile materials designed and produced specifically for medical conditions. The products that need to be used according to the conditions of the medical operation have different physical and chemical properties. From the first centuries to the present day, different textile materials have been used as surgical sutures in accordance with the conditions of the era. Textile fibers, depending on their basic properties such as fineness, length, strength, and elasticity, as well as their chemical composition, have been an important part of the healthcare sector for a very long time. Therefore, the demand for products with natural fiber content has shown a very high increase in recent years.

Medical textiles should be strong and flexible, as well as antitoxic, antiallergic, and biocompatible. Bacteria, fungi, viruses, algae, and other microorganisms exist within the ecological system, but they cause diseases, odors, and material degradation. To prevent this, the application of antimicrobial properties to medical textiles is increasing and rapidly developing. The production of textile materials that inhibit the multiplication of or eliminate microorganisms causing various diseases, produced by applying chemical substances to textile products through various methods, is rapidly increasing (Tech Tex, 2023).

In general, medical textiles can be classified as follows: non-implantable materials: dressing applications; implantable materials: sutures; extracorporeal devices: artificial legs, artificial kidneys, artificial livers; and health and hygiene products:

sanitary pads, diapers (Annapoorani, 2013). Beyond this classification, medical textiles can also be categorized according to their lifespan as single-use or multi-use product groups. Depending on the application, they can also be further classified as fully sterile or hygienic product groups. In addition to traditional products, the variety of medical textile products is increasing every day to meet emerging needs. There are studies supported by governments for research and development activities to produce new products and meet needs. Improvements in healthcare services, increased awareness of effective medical treatments, the growing elderly population, and the increase in the number of surgeries are all contributing to the continuous support for medical textiles in these areas. The global medical textiles market is projected to be worth $32.20 billion in 2022 and to show compound annual growth of 4.3% from 2023 to 2030 (Grand View Research, 2021).

One of the latest applications in medical textiles is nanotextiles, which utilize nanotechnology. The concept of nanotextiles refers to textile products obtained through nanotechnological methods that can find applications in every sector. Nanotechnology is based on the principle of altering the behavior and fundamental structure of matter to improve and enhance the performance of products and processes on the market. Nanotechnological advancements in the medical textiles sector are becoming widespread due to rapid progress and the use of new technologies in both the textile and healthcare sectors.

Examples of nanotechnology applications in textiles include monofilament/multifilament yarns with natural or synthetic content, woven surfaces, knitted products, nonwoven surfaces, or composite fabrics, as well as textile surfaces with reinforced antibacterial properties. Textile fibers have long played a vital role in medicine and healthcare. Fiber-based materials, such as bioglass fiber, are used in tissue engineering to create new bone structures and to promote cell growth and cell formation. Small cylindrical tubes made from biocompatible materials help support and maintain the patency of veins and arteries (Annapoorani, 2013). Products incorporating various electronic devices integrated into comfortable clothing capable of monitoring body functions and metabolism can be cited as examples (Tüylek, 2021). Studies involving the integration of sensors that detect body movements into textile products for motion analysis have also been exemplified (Mattmann et al., 2007).

2. WOUND DRESSINGS

Wound dressings are surfaces made from natural and synthetic materials that contribute to the healing process by maintaining optimal conditions for the treatment of damaged tissues and the regeneration of cells in the same area. Wound dressings are materials used to cover wounds (Abe et al., 2009). In the wound healing process, wound dressings not only accelerate healing but also provide protection against infection. A wound dressing should have hemostatic and highly absorbent properties on the wound surface, be breathable, and prevent microbial growth. Other essential characteristics expected of a wound dressing material include being non-toxic, permeable to liquids and vapors but preventing the passage of microbes and bacteria, and being biocompatible. Due to these properties, wound dressings made from nanofibers can be used in many stages, from surgical operations to wound dressing treatments.

Since the 1980s, wound dressings with various functions that accelerate wound healing have been developed (Anand, 2002). The secretions present in the wound continue to be released during the healing process; therefore, the wound surface needs to be protected from environmentally sourced bacteria and microbes. Nanofibers, thanks to their nano-pores, facilitate the transmission of oxygen and air from the outside while simultaneously helping to remove fluid from the wound, preventing its accumulation on the wound surface. This prevents bacterial growth on the wound surface. Wound dressings used in the wound healing process support the healing process in conjunction with the medications administered during treatment. The use of drugs as extracts in existing nanofiber wound dressings plays a supportive role in cellular development by monitoring drug release times.

Wound dressings used during treatment should be applied practically to the wound surface. To prevent or minimize further damage to the tissue during the healing phases, the dressing should also be easily removable. Furthermore, the dressing should maintain moisture balance for wound healing and should not require frequent changes (Jayakumar, 2011).

The main functions of wound dressings can be summarized as follows: fluid control to prevent leakage of wound fluid, elimination of odors, microbial control to prevent bacterial growth, physical barrier protection against trauma, and space-filling properties to aid healing in deep-seated wounds. In addition, they can clean foreign materials, damaged and infected tissues from the wound, reduce blood loss, prevent adhesion to the wound surface, prevent scarring for aesthetic reasons, maintain a metal ion balance that plays a role in improving cellular activity, and accelerate wound healing (Altay and Başal, 2010). Recent studies have shown that wound dressings produced using electrospinning, a nanofiber production technique, are being used more frequently and are becoming increasingly common. The properties of wound dressings are summarized in Table 1.

Table 1. Required Characteristics of Wound Dressings. (London et al., 1995)

Characteristics of wound dressings	
Essential Characteristics	**Additional features**
To reduce pain.	To be flexible and comfortable.
Non-toxic.	Biodegradable.
Absorbs discharge	Removes easily without adhering to the wound surface
Preventing infection	Easy to implement
To provide a moist environment	To be bioabsorbable
To prevent the wound from coming into contact with contaminants.	To be transparent.
To provide optimum gas permeability, temperature and pH	To have water vapor permeability without allowing bacterial passage

Currently, the most commonly used wound dressings are grouped into five main categories: alginate dressings, polyurethane films, hydrogels, hydrocolloid dressings, and foams (Menaker, 2001). These can be used individually or in combination, depending on the condition of the wound. These developed wound dressings differ according to their suitability for the application area, advantages, and disadvantages. Rezvani Ghomi et al. summurized the classifications, the applications, advantages, and disadvantage of wound dressings as shown in Table 2.

Table 2. Differences in Modern Wound Dressings. (Rezvani Ghomi et al., 2023)

Dressing type	Application	Advantages	Disadvantages
Traditional wound dressings	Protecting wounds from external infections, usually used for woundswith mild extrude or as secondarydressings	Easy application, low cost, and simple manufacturing.	Lack of controllable moistureabsorption from the wound, leaving ittoo dry for timely healing, adhesiveto the wound in the case ofexcessive wound drainage leading tocomplex and painful dressingremoval.
Semi-permeable films	Acute skin burns, injuries, skin defects, catheterization, fixation of stoma,and prevention of pressure ulcers	Maintaining moisture, transparent, elastic , breathable bacterial barrier, and permeable	Not sterile, not suitable for deeperwounds with heavy extrude orpatients with the fragile peri-woundski

Foams	Wounds with moderate to largeamounts of permeate	High absorbing capacity, compatibilitywith wound shape, combined usagewith antimicrobial drugs	Not suitable for dry wounds, demanding frequent changing
Hydrogels	Mostly used for burn wounds but also for traumaticwounds, ulcerations, and bedsores	Elastic, easy application and removal, rehydrating for dry wounds	Excessive water absorbing capacity(70%–90%) may lead to potentialmaceration and bacterial expansion
Nanofibrous mats	Wounds with mild to moderate exudates, Chronic wounds, and burns	Mimicking to skin extracellular matrix, controllable permeability, porosity, and patterning	Reproducibility and scaling up
Hydrocolloids	Wounds with mild to moderate exudates light wounds thatreach up to the dermis layer	Impermeable to watervapor,preventing the spreadof pathogenic microorganisms	Not suitable for infected wounds, hardto keep in place and remove
Alginates	Wounds with heavy oozing fluid, suchas pressure ulcers and various ulcer wounds	Hemostatic, highly absorbent Not suitable for dry wounds, demanding frequent changing	Not suitable for dry wounds, demanding frequent changing

When examining the stages of wound healing and the types of wound dressings to be used according to these stages; in the inflammatory, substrate (preparation) phase, secretion absorbents, alginates, and foams are used. In the proliferation; collagen production phase, hydrocolloids, gels, and hydrogels are used. In the maturation/remodeling phase, hydrocolloid foams and films are used (Altay and Başal, 2010). The selection of the type and size of the care product is carefully evaluated according to the width, depth, microbiological status of the wound, the presence of necrotic tissues, edema, and exudate secretion (Çizmeci, 2008).

3. NANOFIBER

The term "nano" derives from the Greek word "nanos," meaning "dwarf." It is used to describe the size of any physical structure, specifically one billionth of it. Nanostructures, when examined in terms of length, correspond to systems of 10^{-9} meters and 10^{-10} atoms (Özdoğan et al., 2006). Alternatively, the term "nanofiber" is used for nano-sized fibers with a diameter equivalent to one millionth of a physical structure, obtained through various production techniques. Nanofiber sizes are shown in Figure 1. The process, which began with Gilbert (1628) observing the attraction of liquids by electrostatic force, continued with Gray's study of the behavior of water droplets under electrostatic forces. In 1882, Rayleigh stated that when the force caused by surface tension created by the electric field force was overcome, the solution droplet began to flow by separating into fine jets (Doğan, 2012). To determine the force required for the droplet to exit the nozzle, he calculated the maximum load.

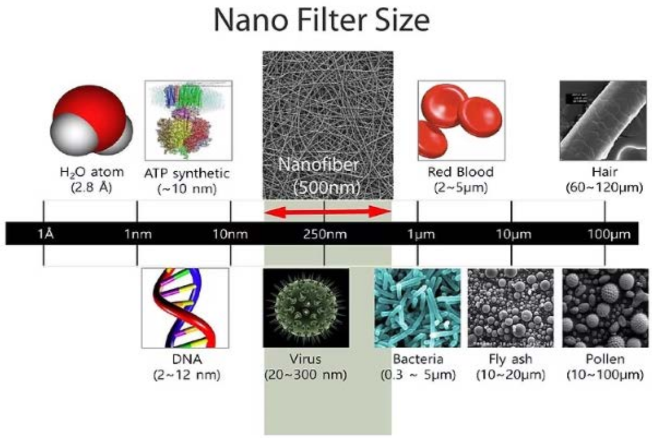

Figure 1. Nanofiber Sizes (İcsmühendislik, 2023)

Doğan (2012) states that the first patents in the electrospinning process belonged to Cooley and Morton (1902), and that from 1934 to 1944, Formhals obtained 11 patents related to these studies, shedding light on many issues. Studies on voltage, electric field, and viscosity affecting solution structure were carried out by Drozin (1955), Taylor (1964), and Simons (1966). In 1964, Taylor introduced the Taylor cone, formed by the electric field force and the polymer solution droplet, to the literature. The investigation of nanofiber surfaces that can be used in the field of filtration began with Simm (1978). The first studies on its usability in the medical field were shown by Martin et al. (1977), How (1985), and Bornat (1987). Fine and Tora (1980) investigated the effect of electrostatic forces and centrifugal force on polyurethane in a rotating vessel to which they applied a high electric field. In 1981, Larrondo and Manley conducted research on electrospinning from melts. The first studies of academic value were initiated by Reneker and his team in the 1990s. The historical development of the electrospinning method after 1990 is shown in Table 3.

Table 3. Historical development of electrospinning method after 1990. (Thenmozhi et al., 2017)

1996–2001	Publications related to working parameters such as solution, medium, and material.
2001–2005	Publications by various researchers from different countries on the introduction of different types of electrospinning instruments, synthesis and characterization of e-spun nanofibers.
2006-Nowadays	During this period, most publications focused on the use of e-spun nanofibers in sensor and tissue engineering applications. Significant applications were achieved in the medical field as drug delivery systems.

In recent years, there has been increasing interest in using this technology to produce nanoscale fibers, particularly for creating nanofiber scaffolds from various natural and synthetic polymers, such as polylactic acid, for tissue engineering (Chong et al., 2007). For example, Yang et al. (2005) produced nanoscale fibers containing polylactic acid, Stankus et al. (2004) polyurethane, Ohgo et al. (2003) silk fibroin, Matthews et al. (2002) collagen, Um et al. (2004) hyaluronic acid, Ma et al. (2005) cellulose, and Chen et al. (2007) chitosan/collagen polymers (Bhardwaj and Kundu, 2010).

3.1. Nanofiber Production Methods

Many methods have been developed for nanofiber production. Examples of these methods include self-assembly, template synthesis, spunbonding, drawing, phase separation, bicomponent extrusion, meltblown, and electrospinning (Alghoraibi, I., and Alomari, 2018). Table 4 shows a comparison of different nanofiber production techniques.

Table 4. Comparison of different nanofiber production techniques (Sarbatly, and Chiam, 2022)

Technique	Advantages	Disadvantage
Needle electrospinning	Scalable, feasible of fiber dimension control, fibers are long and continuous	Solvent recovery issues, low productivity, instable jetting, high voltage requirement
Needleless electrospinning	Scalable, feasible of fiber dimension control, fibers are long and continuous, high productivity	Solvent recovery issues, high voltage requirement
Melt-blowing	Scalable, feasible of fiber dimension control, fibers are long and continuous, high productivity, solvent recovery is not required	Number of suitable polymers is limited, high temperature requirement
Melt-blending extrusion	Scalable, feasible of fiber dimension control, fibers are long and continuous, high productivity, solvent recovery is not required	Number of suitable polymers is limited, high temperature requirement
Drawing	Simple process	Low scalability, incapable of fiber dimension control, discontinuous process
Centrifugal force spinning	Scalable, feasible of fiber dimension control, high voltage is not required	Require high temperature
Phase inversion	Simple equipment	Low scalability, incapable of fiber dimension control, limited to selective polymers
Template synthesis	Easy to modify the fiber diameter by using different size of template	Complex process
Self-assembly	Easy to obtain smaller nanofibers	Low scalability, incapable of fiber dimension control, complex proces

The most common spinning methods used for nanofibers in medical textiles are described below:

Template synthesis; Nanofibers with a fiber diameter of 3-15 nm can be produced using a template or mold (Doğan, 2012).

Phase separation; In this method, nanofibers with a fiber diameter of 50-500 nm are obtained by the separation of phases due to physical incompatibility. The process consists of five stages. These are, in order: dissolving the polymers, gelling, separating the solvent, freezing, and cold drying (Kozanoğlu, 2006).

Self-assembly; Nanofibers with a fiber diameter in the range of 7-100 nm can be produced. In this method, nano-sized fibers can be obtained by forming simple blocks from small molecules (Shimizu et al., 2014).

Spinning Method; With the help of a micromanipulator, the pipette is dipped into the line where the solution contacts the surface, and by pulling it out of the liquid at a certain speed, the solvent evaporates rapidly and the fiber structure is formed. Very small diameter fibers cannot be produced and have not found many applications (Oflaz, 2016).

The meltblown method is a method for producing small diameter fibers, theoretically between 0.5 and 30 µm, and in reality between 2-7 µm. Filaments were ejected from nozzles with the help of high-temperature hot air. This provides a fibrillated nonwoven structure. Therefore, it is preferred for the production of nonwoven fabric surfaces. It is generally used in thermoplastic fibers such as PET, PP, and PA 6 (Kozanoğlu, 2006).

The bicomponent method is a production method carried out by passing two different polymers through the same nozzle to obtain a single fiber. When the cross-sectional areas of bicomponent fibers are examined, bicomponent fibers are found in interwoven, side-by-side, island in the sea, or sliced cake models(Figure2.11)(Kozanoğlu,2006).

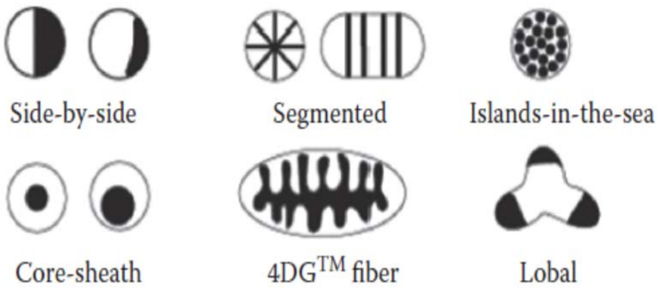

Figure 2. Bicomponent Fibers (Kiron., 2021)

Electrospinning; Due to its ease of use, it is the most preferred method in medical applications. It is a single-step spinning method that allows for the easy production of fibers with nanometer diameters. In principle, it can be explained as follows: by applying a high voltage force from a power source, the resistance struggle between electrostatic and capillary forces in the polymer solution is overcome, allowing the polymer solution to adhere as fibers on a collector in the form of small jets (Doğan, 2012). The electrospinning method uses an electric current with a voltage ranging from 5 kV to 30 kV, which eliminates the surface tension of a polymer. The polymer solution, having overcome its surface tension, can now be produced in nanofiber form. The process can be explained as the polymer solution passing through a specially designed and manufactured jet nozzle, traversing the distance between the nozzle and the collector, and reaching a grounded collector opposite the nozzle (Özdoğan et al., 2006). In electrospinning, many factors influence the morphological structure and diameter of the nanofibers produced. Solution concentration, viscosity, conductivity, polymer molecular weight, ambient temperature and humidity, applied voltage, feed rate, collector type, etc., are some of the main examples (Uçar et al., 2011). By thoroughly understanding and optimizing the effects of the parameters classified in Table 5 on fiber morphology, it is possible to obtain uniform nanofibers with the desired morphology.

Table 5. Parameters affecting the electrospinning process. (Akın et al., 2020)

Solution parameters	Process parameters	Environmental parameters
Solvent type, Dielectric constant of the solvent Solution viscosity, Conductivity of the solution Polymer molecular weight, Solution temperature, Surface tension of the solution	Voltage Distance between needle and collector Solution flow rate Collector type/ geometry	Temperature Moisture Pressure

The high surface area/volume ratio of nanofibers offers a large area for loading active pharmaceutical substances. This feature allows for controlled drug release to the wound area, increasing treatment efficiency (Öztaş, 2021). When biodegradable polymers are used, absorption by the body can be ensured without the need to remove the dressing after wound healing. Among synthetic polymers, PCL, PLA, and PVA are the most frequently used materials in electrospinning studies (Tosun and Aydın, 2025). Natural polymers such as chitosan, gelatin, and collagen can be mixed with synthetics to increase cell interaction (Pancur et al., 2022). Adding nanosilver or antibiotics to impart antibacterial properties during the production process is a common approach. With technological advancements, needleless electrospinning methods are increasing mass production capacity (Zahedi et al., 2010). Thanks to modern devices, the thickness and texture of nanofiber surfaces can be precisely controlled. In conclusion, electrospinning is the most capable production technique offering customizable and multifunctional structures for medical textiles.

3.2. Application Areas of Nanofibers

Nanofiber technology, which has gained significant momentum with the introduction of nanotechnology into our lives, offers much higher-performance structures compared to traditional textile products. Thanks to this technology, fabrics can be given superior properties such as stain resistance, water repellency, antibacterial properties, drug release, high durability, and heat resistance. At the heart of all these innovations lies inspiration from nature; indeed, the silkworm's fiber weaving technique, the water-repellent surface of the lotus flower, and extracts of medicinal plants directly guide the development of nanofibers and their functionalization in a wide variety of fields. The fact that nanofibers can be produced using numerous manufacturing techniques and combined with many polymers offers significant advantages in many fields. Examples of nanofiber application areas include medical prostheses, vascular grafts, wound dressing surfaces, telemedicine applications, cartilage and tissue scaffold applications in the biomedical field; plant protection and development, and productivity enhancement in agriculture; insulation materials, conductive and semiconductor materials, optical applications, and sensors in the electrical and energy fields; gas-liquid filtration applications; protective clothing design; solar and light panels; and composite material production. Furthermore, research in energy storage and transmission, environmental protection applications, and information transfer process support has gained significant momentum. Examples of nanofiber application areas are shown in Figure 3. During their use in these fields, advanced manufacturing techniques are employed from raw materials to the final product, imparting extra functional properties to the nanofibers.

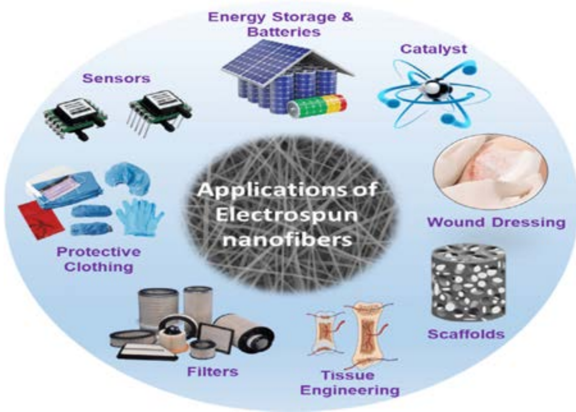

Figure 3. Applications of Electrospun nanofibers (Nathanael and Oh. ,2021)

3.4. Applications of Nanofiber Wound Dressings

Nanofiber wound dressings exhibit therapeutic properties across a wide range of conditions, including chronic wounds to burns. Their primary function is to accelerate the epithelialization process by keeping the wound bed moist (Rieger et al., 2013). Their morphology, mimicking the extracellular matrix (ECM), allows fibroblasts and keratinocytes to adhere to and proliferate on the surface (Zhang et al., 2005). Unlike conventional dressings, nanofibers do not adhere to the wound and do not damage newly formed tissue during dressing changes. Antibacterial properties of nanofibers can be enhanced by integrating metallic nanoparticles such as silver, copper, or zinc into the nanofibers (Unnithan et al., 2012). Encapsulating plant extracts and essential oils in nanofibers offers natural and non-toxic alternative treatment pathways. In difficult-to-heal cases such as diabetic foot ulcers, growth factor-loaded nanofibers trigger tissue repair (Shi et al., 2010). The high porosity of nanofiber structures allows for effective removal of wound exudate. This protects wound edges by minimizing the risk of maceration around the wound. Thanks to their gas permeability, anaerobic bacterial growth is prevented in the wound area

(Morris, H., & Murray, R. (2022). Nanofibers also exhibit a hemostatic effect by accelerating blood clotting due to their high surface contact. Their biocompatible nature balances the inflammatory process by preventing the body from reacting to foreign substances. Smart wound dressings can detect pH changes in the wound area and change color in case of infection (Mele, 2016). This functionality helps healthcare personnel determine the correct intervention time. Composite nanofiber structures can offer multi-stage treatment by providing different drug release rates in different layers. Nanofiber applications in medical textiles are creating a revolutionary change, especially in regenerative medicine and controlled drug release systems. Clinical studies have shown that the use of nanofibers shortens wound healing time by up to 40% compared to standard gauze. Greiner and Wendorff (2008) investigated the usability of a surface created from nanofibers of type I collagen produced by electrospinning as a wound dressing. In tests conducted on mice, they stated that the wound dressing containing type I collagen showed a rapid healing performance when compared to commercially available wound dressings. Üstündağ et al. (2010) demonstrated the usability of the surface produced by producing alginate nanofibers because its performance characteristics were better than drug-impregnated gauze and similar to Bactigras, an antibacterial dressing. Nanofiber socks and dressings containing antifungal agents offer the possibility of long-term and dose-controlled treatment against fungal infections (Du, L., et al., 2024). Turgut (2018) produced fibers from a polymer solution by mixing polycaprolactone (PCL) and gelatin (gel) polymers with acetic acid/formic acid, and according to the drug release test results of these fibers, a large portion of vitamin B12 was released in the first 50 minutes. Hernández and Martin (2021) stated that scaffold composition, and morphology are, is an important parameter in the production of bioactive wound dressings. They investigated the fabrication of electrospun wound dressings based on collagen and its blends for skin tissue engineering applications. This investigation indicated that collagen surface modifications on pure collagen, collagen blends, and nanofiber mats have high potential in facilitating healing (Hermandez and Martin 2021). The flexibility and lightness of nanofibers allow for treatment without restricting the patient's mobility (Zhumagaziyeva, A. (2021). Therefore, many studies have been conducted the field of tissue engineering. Balusamy et al. (2020) conducted various studies to demonstrate the usability of nanofibers obtained by electrospinning in tissue engineering. As a result of these studies, they showed that nanofibers have many superior properties such as having an interconnected porous structure, application to a large surface area, ability to serve different tasks, compatibility or differentiation with cellular structures, and ease of adding extra properties, as well as high mechanical performance values. With the expectation that new positive attributes will be added to all these features every day, it has been stated that nanofibers will find more applications in both wound healing and tissue engineering. Scaffolds used in skin tissue engineering represent the most advanced application level of nanofibers. Stem cells implanted on these scaffolds prepare the ground for new skin formation in the treatment of deep burns. In bone tissue engineering, hydroxyapatite-reinforced nanofiber scaffolds accelerate bone repair by increasing osteoblast adhesion (Chen et al., 2019). In recent years, nanofiber filters in antiviral masks and protective clothing have prevented aerosol-borne pathogens (Naragund and Panda, 2022). In periodontal treatment, nanofiber barrier membranes optimize Guided Tissue Regeneration (RTR) and Guided Bone Regeneration (RTR) processes by preventing the migration of gingival epithelial cells into the slow-healing bone tissue. This technology delivers successful results by enabling the regeneration of supporting tissues in cases of gingival recession (Santos et al., 2023). Because common anticancer drugs used in chemotherapy are associated with serious side effects due to high doses and also damage normal cells, controlled and continuous drug release provides benefits. Anticancer drug-loaded nanofibers used for this purpose have shown significant results by enabling longer drug preservation and achieving results with less drug (Arabacı, G., et al., 2023). In cosmetic textiles, face masks containing vitamins and collagen with nanofibers allow active ingredients to penetrate deeper into the skin (Hu, J., et al., 2024). In ophthalmology, drug-loaded nanofiber contact lenses provide more stable bioavailability in glaucoma treatment compared to eye drops (Shoushtari, F. S., et al., 2024).

4. CONCLUSION

In conclusion, nanofiber wound dressings, one of the most innovative solutions that nanotechnology has brought to the field of biomedicine, have initiated a revolutionary era in modern wound care thanks to their high surface area/volume ratios and morphological structures that mimic the natural extracellular matrix (ECM). Today, these dressings go beyond being merely a passive barrier protecting the wound from external factors; they are successfully applied as active and intelligent systems that enable the controlled release of therapeutic agents such as antibiotics, growth factors, silver nanoparticles, and plant extracts. Their ability to effectively remove exudate, provide gas permeability, and support cell proliferation makes these materials a step ahead in clinical practice for the treatment of chronic, diabetic, and burned wounds. However, despite the enormous potential offered by this technology, critical structural challenges remain to be overcome in translating laboratory-scale successes into industrial production and clarifying long-term in vivo biocompatibility and toxicity profiles of these nanomaterials. The future of nanofiber wound dressings lies in. This process will be shaped by the inclusion of "smart" biosensor integrated systems that can respond in real time to changes in wound pH, temperature, or enzyme levels, and 3D bioprinting technologies that support patient-specific cellular therapies. In the coming period, the development of multifunctional nano-composites and the acceleration of multicenter clinical trials will enable these new generation dressings to completely replace traditional treatment methods. Nanofibers integrated with 3D bioprinters are expected to become the standard in personalized wound treatments. Ultimately, these advanced technology products, with optimized biodegradable and bioactive properties, will become one of the most powerful tools in regenerative medicine, playing a key role in improving patient quality of life and alleviating the global health burden. In conclusion, nanofibers are "smart" and "effective" solutions replacing traditional methods in the medical textile sector.

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CIRCULAR ECONOMY AND SUSTAINABILITY PERCEPTION IN THE CARPET INDUSTRY

Gonca ALAN[1]

1. INTRODUCTION

The traditional linear economy operates on a "take-make-dispose" model, characterized by the extraction of raw materials, product manufacturing, and subsequent waste generation. Resource intensity triggers ecological imbalance and operational waste. In response, the circular economy provides a framework to sustain economic development while minimizing additional resource depletion. By optimizing material efficiency and reintegrating waste streams back into the production cycle as secondary inputs, this model aims to create a closed-loop system that ensures long-term environmental and economical benign applications (Chen et al., 2021; Lamba et al.,2024). Traditionally, textile production relies on the high-volume extraction of virgin fibers, leading to significant resource depletion and post-consumer waste accumulation in landfills. To address these systemic inefficiencies, the circular textile economy emphasizes the adoption of closed-loop manufacturing, where materials are designed for longevity, disassembly, and recyclability. By reintegrating textile waste as high-quality secondary raw materials and optimizing resource efficiency throughout the supply chain. This model allows for economic growth without the constant need for new raw materials (Das et al., 2025;Ramirez-Escamilla et al., 2024).

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Figure 1. Circular Economy Constituents (Url1)

The circular economy is based on three core principles: eliminating waste and pollution, maintaining products and materials at their highest value, and regenerating natural systems. Most economies still follow a linear 'take-make-waste' model, where products are designed for disposal rather than recovery. This traditional approach leads to rapid material degradation, forcing reliance on landfills or incineration. Because global resources are limited, these linear systems are inherently unstable and fail to support long-term sustainability. Additionally, the growth of heavy industries; such as metal plating, metallurgy, and battery manufacturing, has significantly increased the release of hazardous chemicals and pollutants into the environment. The second principle of the circular economy focuses on the continuous circulation of materials to maintain their maximum functional and economic value. In this framework, waste is treated as a design flaw rather than an unavoidable outcome. This model requires a 'design-for-circularity' approach, where the main engineering goal is to optimize the product's end-of-life (EoL) recovery. By prioritizing high-value recovery, the model ensures the continuous reintegration of secondary raw materials into the production cycle (Parvaresh& Amini, 2024;Reike et al., 2023). The third principle focuses on the regeneration of natural systems by replacing extractive models with restorative industrial cycles. This shift prioritizes biological renewal over resource depletion, ensuring that economic activities enhance rather than degrade ecosystem health. Ultimately, aligning industrial outputs with natural cycles provides a systemic solution to mitigate climate change, biodiversity loss, and global pollution.

The implementation of the circular economy yields superior sustainability performance compared to the traditional linear model. In this theoretical framework, sustainability is defined as developmental progress that fulfills contemporary societal requirements without compromising the capacity of future generations to satisfy their own needs. Sustainability requires integrating economic, social, and environmental imperatives into core system architecture. Consequently, organizational resilience and market viability depend on the performance of sustainable supply chain management (SSCM) frameworks. To remain competitive, organizations need to improve their ability to create eco-friendly products and innovate. This change matches production with environmental limits, lowering risks from resource shortages and new laws. Sustainability goes beyond eco-friendly production to encompass a comprehensive framework of social equity, environmental integrity, and economic resilience (Abtew et al., 2025; Rahaman&Khan, 2025). Fragmented strategies are insufficient; true progress requires a systematic integration of all three constituents. Consequently, industrial transformation must align economic viability with social responsibility and ecological restoration. To achieve systemic balance, organizations should focus on a triple-bottom-line approach, optimizing value across environmental, social, and economic dimensions in every strategic decision. Sustainability acts as a powerful tool to improve the textile industry by restoring nature, using resources wisely, and creating a fair society. By balancing environmental, economic, and social goals, the sector can build a stronger and more reliable future. This positive approach ensures that industrial growth works in harmony with the planet, turning environmental challenges into opportunities for innovation and long-term success. Environmental sustainability in the textile industry focuses on the responsible management of natural resources to ensure long-term ecological balance. By aligning production with the earth's regenerative capacity, the sector can transform its environmental impact into a positive contribution to planetary health. This approach emphasizes the adoption of safe chemical alternatives, the implementation of zero-waste manufacturing, and the development of durable, recyclable products. Furthermore, prioritizing carbon neutrality and water conservation enables the industry to foster a resilient ecosystem where industrial growth and nature thrive together. Economic sustainability helps the textile sector stay profitable and stable over time by balancing industrial growth with resource efficiency. This approach promotes resilient business models that open new market opportunities and innovation. By investing in green technologies and supporting local production, the industry enhances its global competitiveness while reducing import dependency. Ultimately, these strategies empower small and medium-sized enterprises (SMEs) and generate stable employment, ensuring that economic success contributes to a benign and more sustainable future. Effective sustainability involves embedding strategic objectives into the firm’s core operations, replacing isolated initiatives with a comprehensive organizational shift. Sustainable development necessitates the structural integration of ecological and social parameters into core operational frameworks, rather than employing sustainability as a separated mechanism. Strategic integration optimizes operational viability and facilitates sustained value generation.

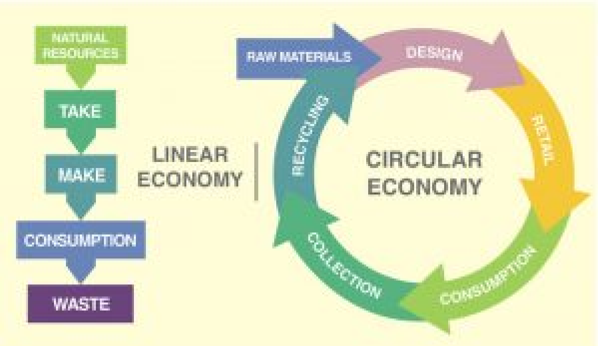

Figure 2. From Linear to Circular Economy (Url 2)

Sustainability and the circular economy are linked through a functional synergy, where sustainability represents the theoretical objective of systemic balance and the circular economy provides the technical design to operate the process. While sustainability serves as the foundational paradigm for long-term socio-ecological balance, the circular economy functions as the operational framework to achieve this state by transitioning from linear resource depletion to closed-loop regenerative systems. In other words, sustainability defines the systemic objective of multi-dimensional stability, whereas the circular economy provides the technical methodology for resource optimization. The circular economy model serves as a vital methodology for synchronizing industrial throughput with planetary boundaries by optimizing material productivity and eliminating systemic inefficiency. Consequently, circularity is the essential mechanism through which the abstract goals of sustainability are converted into measurable environmental outcomes.

The circular economy offers a transformative model for the textile industry by replacing the traditional "take-make-dispose" system with a closed-loop framework. In this approach, resources are kept in use for as long as possible through systematic reuse, repurposing, and recycling. By transitioning from linear manufacturing, the sector can achieve growth while reducing reliance on raw materials and effectively enhance environmental performance and promote ecological preservation.

As one of the world's most resource-intensive industries, the textile sector faces critical challenges, including overproduction, water scarcity, and chemical pollution. Transitioning to a circular model has become a strategic necessity to address these issues. Through innovative design and efficient material management, businesses can eliminate waste and ensure long-term ecological and economic viability.

Figure 3. Basic Principles of Circular Economy (Url 3)

A circular approach is essential for the textile industry due to several key factors:

Resource Optimization: Conventional textile manufacturing generates substantial residual output that typically exceeds landfill capacity. A circular framework mitigates this by integrating systematic recycling and repurposing, thereby minimizing material loss and environmental accumulation.

Material Productivity: Implementing closed-loop fiber cycles minimizes the consumption of primary resources, leading to improved cost structures and reduced environmental pressure.

Environmental Regeneration: Systematic waste reduction and enhanced material recovery directly lower total carbon intensity. These actions align sectoral outputs with global climate stabilization goals and improve overall environmental performance.

Market Alignment: Increasing ecological awareness among consumers drives the demand for transparent and responsible supply chains. Organizations that integrate sustainable frameworks gain a competitive advantage by meeting these evolving expectations and strengthening long-term brand equity.

Strategic Innovation: The transition to circularity catalyzes advancements in product design, material science, and recovery technologies. Furthermore, it facilitates the emergence of novel business models, such as "Product-as-a-Service" or upcycling ventures, creating diversified value streams.

Circular frameworks enhance profitability by maximizing material utilization and reducing operational overheads. By aligning production with the increasing demand for sustainable textiles, businesses can access emerging market segments and diversify their revenue streams. The transition to circularity catalyzes job creation across specialized sectors, such as advanced recycling, product restoration, and sustainable design. This shift promotes workforce development, equipping employees with future-ready skills and driving regional economic growth. In an era of informed consumption, commitment to circular principles strengthens brand loyalty and builds long-term consumer trust. Demonstrating ethical leadership allows businesses to differentiate themselves in a competitive global market. A circular approach encourages cross-sector partnerships to develop scalable solutions for material recyclability. This collaborative environment cultivates transparency throughout the supply chain, ensuring accountability and reinforcing the confidence of all interest groups (Ghosh et al., 2025; Ho&Lin, 2024; Pranta et al., 2025; Luoma et al., 2022).

2. GOVERNANCE AND REGULATORY FRAMEWORKS ON CIRCULAR ECONOMY

Public policies and regulatory instruments are essential for accelerating the transition to a circular textile economy. These frameworks provide the necessary structure to guide industrial operations toward sustainability, effectively minimizing waste and optimizing resource productivity through legislative alignment. As a core component of the European Green Deal, this strategy establishes a comprehensive regulatory framework to transform the textile value chain. It introduces mandatory Eco-design Standards to ensure products are durable, repairable, and recyclable from the design phase. A key innovation is the Digital Product Passport (DPP), which enhances supply chain transparency by providing accessible data on material composition and environmental impact throughout the product's life. Furthermore, the strategy implements Extended Producer Responsibility (EPR) schemes, requiring manufacturers to take financial and operational accountability for the end-of-life management of their products, thereby incentivizing waste prevention and circular material recovery. The Waste Framework Directive (WFD) serves as the primary legislative instrument for waste management within the European Union, establishing a legal hierarchy to minimize environmental externalities and maximize resource recovery. Its core objective is to decouple economic growth from waste generation by prioritizing prevention and promoting the transition toward a high-efficiency recycling society (Cramer, 2022; Alberich et al, 2023; Pimenow, 2026; Anania, 2025; Kylänlahti-Harmaala, 2023).

In order to accelerate the transition toward a circular textile economy, the following critical areas require systemic improvement:

Standardization of Regulatory Frameworks: There is a fundamental need to align sustainability standards across regions to eliminate fragmented practices and ensure global operational consistency.

Promoting Advanced and Innovative Technologies: Providing targeted financial instruments is essential to stimulate the development and adoption of advanced, sustainable textile technologies.

Expansion of Consumer Awareness: Enhancing public awareness regarding the ecological footprint of textiles is vital to shift consumption patterns toward sustainable fashion.

Infrastructure for Circular Business Models: Strengthening the support for second-hand markets and take-back schemes is necessary to facilitate effective reuse, repair, and recycling cycles.

Global Knowledge Exchange: International cooperation must be prioritized to share technical resources and best practices, ensuring a unified global response to environmental challenges.

The transtition toward a circular textile economy is more than a technical update; it is a complete optimization of how we use materials and manage their lifecycles. Real success requires integrating circular principles directly into production strategies, rather than relying on small, isolated changes. At this stage, the industry must focus on technical innovation and responsible material management. By ensuring supply chain transparency, the textile sector can move from a linear "use-and-waste" model to a regenerative closed-loop system. Ultimately, the industry’s future depends not on the speed of production, but on the quality and integrity of its recycled resource streams.

3. EVALUATION OF MATERIAL SOURCES FOR CARPET MANUFACTURING FROM AN ASPECT OF SUSTAINABILITY

In addition to commercial applications, global household demand for the carpet sector is experiencing a significant upward trajectory. This expansion is primarily driven by accelerating urbanization rates and rising levels of disposable income. Furthermore, the sustained growth of the construction industry is projected to stabilize long-term demand for home interior products, including carpets and rugs. In recent years, the heightened focus on architectural aesthetics, coupled with a shifting consumer preference toward eco-friendly materials and contemporary designs, has further stimulated overall market growth (Üstün, 2026).

In the context of textile engineering and sustainable interior design, the selection of floor covering materials necessitates a comprehensive evaluation of life cycle assessments (LCA) and the principles of the circular economy.

True sustainability in carpeting goes beyond the basic utilization of recycled content; it requires a "cradle-to-cradle" approach, where materials are engineered for perpetual reclamation and reintegration into subsequent production cycles without qualitative degradation. The "cradle-to-cradle" (C2C) framework is a regenerative design philosophy that replaces the traditional linear "take-make-waste" model with a circular economy approach. Rather than viewing a product's lifecycle as a path leading to a landfill—often termed "cradle-to-grave"—this system envisions a continuous loop where materials are perpetually repurposed (Cunningham & Miller, 2022; Gade, 2026, Luthin et al., 2024).

The core logic of this model relies on three fundamental pillars. First, it eliminates the concept of waste by treating every industrial output as a nutrient for a new process. Materials are categorized into two distinct cycles: the biological cycle, consisting of biodegradable substances like wool or jute that safely return to the environment, and the technical cycle, which involves synthetic materials like Nylon 6 that can be recycled infinitely without losing their structural integrity. Second, the framework prioritizes material health, ensuring that all components are free from toxic chemicals, such as heavy metals or volatile organic compounds (VOCs). Finally, C2C emphasizes a "design for disassembly" strategy, where products are engineered to be easily separated into their original components at the end of their functional life. To sum up, a cradle-to-cradle certified product, such as a sustainable carpet, is manufactured using renewable energy and non-toxic materials. When it reaches the end of its use, it does not become waste; instead, it either biodegrades to nourish the soil or returns to the factory to be transformed into high-quality new fibers (Bozkurt et al., 2025, Üzümcü & Sarı, 2025).

In the specialized field of carpet manufacturing, wool stands out as a premier protein-based biopolymer, offering a unique combination of ecological integrity and high-performance technical characteristics. Chemically, wool is a fully renewable and biodegradable fiber, featuring a complex molecular architecture that allows it to act as a natural air filter. In carpet applications, this structure facilitates the adsorption of indoor volatile organic compounds (VOCs), significantly improving air quality within living spaces.

From a mechanical standpoint, the inherent resilience of wool fibers with their natural helical coil, is a critical advantage for floor coverings. This structural elasticity ensures that wool carpets maintain their pile height and texture even under heavy foot traffic, providing exceptional durability. Additionally, the fiber's natural protective layer offers inherent stain resistance, which extends the carpet's functional lifespan and eliminates the requirement for harsh chemical finishes. By integrating these natural properties, wool-based carpets represent a superior technical solution that balances long-term physical performance with environmental responsibility.

Beyond animal-derived fibers, the carpet industry extensively utilizes plant-based cellulosic materials such as jute, sisal, seagrass, and organic cotton, each offering distinct physicochemical profiles for textile applications. Jute, a lignocellulosic bast fiber, is highly valued for its high tensile strength and thermal insulation properties; however, its primary disadvantage lies in its high hygroscopicity, which makes it susceptible to microbial degradation in humid environments. Sisal, extracted from the Agave sisalana plant, is characterized by its superior mechanical toughness and resistance to saltwater corrosion, though its coarse and rigid texture can limit tactile comfort in residential settings.

Seagrass fibers offer a unique chemical advantage due to their non-porous outer skin, which provides natural impermeability to stains and moisture; nonetheless, this same density makes the fiber virtually impossible to dye, restricting the aesthetic range to natural ochre tones. Lastly, organic cotton is prized for its high cellulose purity and exceptional skin-friendliness, offering a soft hand-feel that other plant fibers lack. Despite this, its relatively low elastic recovery often leads to dimensional instability and crushing under heavy furniture loads. Together, these botanical fibers represent a versatile palette of sustainable substrates, provided that their specific physical limitations are mitigated through strategic blending or specialized backing techniques.

In the context of synthetic textile substrates, recycled polyethylene terephthalate (rPET) derived from post-consumer sources—such as beverage containers and food packaging—is increasingly integrated into carpet manufacturing. From a technical standpoint, rPET fibers offer a significant environmental advantage by diverting plastic waste from landfills and requiring lower energy consumption during the extrusion process compared to virgin polyester. Chemically, these fibers exhibit excellent hydrophobic properties and inherent colorfastness, making them resistant to water-based stains and UV degradation.

However, the utilization of rPET in floor coverings presents critical technical and ecological challenges. First, from a circular economy perspective, the end-of-life recyclability of rPET carpets is severely hindered by the presence of multi-material backings and chemical adhesives. The mechanical separation of these heterogeneous components is technically complex and often economically unviable, resulting in a "downcycling" trajectory rather than a closed-loop recovery. Second, during the mechanical stress of regular use and maintenance, these synthetic filaments are prone to microfiber shedding. These microplastics are released into the indoor environment, contributing to particulate pollution and raising concerns regarding long-term inhalation exposure. Consequently, while rPET promotes the initial reuse of plastic waste, its performance within a truly sustainable lifecycle remains limited compared to natural biopolymers.

Currently, the carpet industry relies heavily on synthetic polymers such as nylon, polypropylene, and polyester due to their high performance-to-cost ratio and exceptional physical durability. From a manufacturing standpoint, these petroleum-based fibers offer immense versatility, including high abrasion resistance and ease of mass production. However, from a sustainability perspective, these materials present certain environmental challenges that the industry is actively working to mitigate. The production of these synthetic fibers is an energy-intensive process that involves the extraction of fossil fuels, resulting in a measurable carbon footprint and the emission of greenhouse gases during polymerization and extrusion. Additionally, while these materials provide long-lasting functional use, they are prone to fiber shedding, which can introduce synthetic particulates into the indoor environment. Unlike natural biopolymers, these conventional synthetics are not inherently biodegradable, making their end-of-life management a critical focal point for current research into advanced recycling technologies and carbon-neutral production methods (Lawson, 2023; Watson & Warnock, 2003).

The utilization of polyamide (PA) fibers, commonly referred to as nylon, represents a cornerstone in high-performance carpet manufacturing due to a unique combination of mechanical durability and aesthetic versatility. From a textile engineering perspective, the primary advantage of polyamide lies in its exceptional elastic recovery and structural memory.

This resilience allows the carpet pile to withstand significant compressive loads and high foot traffic without permanent deformation or matting. Furthermore, the molecular structure of polyamide, characterized by its high affinity for acid dyestuffs, facilitates superior color exhaustion and fastness, enabling the production of vibrant, intricate designs that resist fading over time.

Technically, however, the material exhibits certain inherent limitations. Polyamide is semi-crystalline and relatively hygroscopic material. Hereby, it can absorb atmospheric moisture, which may act as a plasticizer and potentially compromise the dimensional stability of the textile under fluctuating humidity levels. Moreover, its low electrical conductivity necessitates the integration of conductive filaments or topical anti-static treatments to mitigate the accumulation of electrostatic charges. While its thermal stability is superior to that of polyolefins, it remains susceptible to oxidative degradation when exposed to concentrated bleaching agents or prolonged ultraviolet radiation.

From an environmental and circular economy standpoint, polyamide presents a complex ecological profile. The traditional synthesis of polyamide is energy-intensive and reliant on petrochemical precursors, contributing to a substantial carbon footprint. Additionally, the non-biodegradable nature of the polymer poses long-term waste management challenges, as post-consumer carpets often end up in landfills where they persist for centuries. Whereas; a significant technical benefit is the closed-loop recyclability of Polyamide 6. Through chemical depolymerization, PA6 can be reverted to its monomer, caprolactam, and repolymerized into "virgin-quality" fiber without losing mechanical integrity—a process that exemplifies true circularity.

Polyester (Polyethylene Terephthalate-PET) fibers in carpet manufacturing has gained a significant strategic increase, positioned as a cost-effective and ecologically benign alternative to polyamide. The major advantage of PET can be stated as the hydrophobic nature, which provides superior topical stain resistance without the extensive need for chemical treatments. Chemically, polyester lacks the dye sites required by many common stains (such as food dyes), making it an ideal candidate for residential environments. Additionally, advancements in extrusion technology have significantly improved the "hand" or softness of polyester yarns, allowing manufacturers to produce high-density, luxurious textures that rival natural fibers in tactile quality.

However, the technical performance of polyester is often constrained by its inferior mechanical resilience compared to polyamide. PET fibers possess a lower elastic recovery rate; under prolonged static loading or heavy foot traffic, the fiber structure undergoes greater plastic deformation, leading to visible "shading" or permanent matting of the carpet pile. Furthermore, because polyester is typically solution-dyed or dyed using disperse dyes at high temperatures, achieving the same level of intricate color depth and post-production versatility as acid-dyed nylon can be technically challenging. Its affinity for oil-based substances also makes it more susceptible to "soiling," where oily residues bond to the fiber surface and attract particulate matter.

Regarding environmental and circular economy factors, polyester is at a primary point for sustainable transition within the industry. A substantial portion of PET carpet fiber is currently produced from post-consumer recycled content, primarily diverted from the beverage packaging industry (rPET). This established recycling infrastructure significantly reduces the demand for virgin petrochemical precursors and lowers the overall carbon intensity of the production cycle. The 'cradle-to-cradle' circularity of polyester represents a dynamic frontier in sustainable textile engineering; the seamless conversion of PET bottles into high-performance carpet fibers serves as a benchmark for resource diversion and waste valorization. By effectively utilizing post-consumer streams, polyester strengthens the bridge between the packaging and flooring industries, significantly reducing the reliance on virgin materials. Moreover, the integration of emerging thermochemical recycling technologies promises to further refine this loop, ensuring that end-of-life carpets are increasingly viewed as valuable feedstock rather than waste. This transition toward advanced recovery methods highlights polyester's role as a cornerstone of the industry's green evolution, fostering a regenerative lifecycle that prioritizes carbon footprint reduction and long-term environmental stewardship.

The utilization of polyolefin fibers—predominantly polypropylene (PP)—in carpet manufacturing is characterized by a unique combination of chemical inertness and cost-effectiveness. The main advantage of polyolefins is their exceptional hydrophobicity and zero moisture regain. This inherent moisture resistance makes the fibers naturally resistant to water-based stains and prevents the growth of mold or mildew, positioning them as an ideal choice for outdoor environments and moisture-prone areas. Furthermore, polyolefins are typically solution-dyed during the extrusion process, resulting in superior colorfastness against harsh chemicals and ultraviolet (UV) radiation, as the pigments are integrated directly into the polymer matrix. However, the technical utility of polyolefins is constrained by significant mechanical and thermal limitations. Due to their relatively low melting point and inferior elastic recovery, polyolefin fibers exhibit poor resilience under heavy static or dynamic loads. This leads to accelerated "crushing" and permanent deformation of the carpet pile compared to polyamide or polyester counterparts. Additionally, their low surface energy makes them highly oleophilic, meaning they attract and retain oil-based soils, which can be difficult to remove and may accelerate the aesthetic degradation of the textile surface over time. From an environmental and circular economy standpoint, polyolefins offer both opportunities and significant challenges. From a sustainability perspective, polyolefins are exceptionally advantageous, boasting the lowest carbon footprint during the initial synthesis and extrusion phases among all major synthetic fibers. Their nature as a high-purity thermoplastic makes them a prime candidate for efficient mechanical recycling, ensuring that with evolving collection infrastructures, these materials can be seamlessly reintegrated into production cycles. Consequently, polyolefins stand as a pivotal element in the transition toward energy-efficient, low-impact, and fully regenerable textile systems.

The transition from historical multi-material carpet architectures toward innovative mono-material designs represents a significant leap in textile engineering. While traditional carpets combine different materials like nylon, polyester, and latex, the modern multi-material approach is now being redesigned to support a circular economy. By choosing compatible material groups, manufacturers can create high-performance products that are easier to separate and recycle at the end of their life. This strategy reduces the need for new raw materials and minimizes industrial waste. Furthermore, using recycled components within these multi-material structures significantly lowers the carbon footprint of production. Therefore, focusing on smart material combinations is a vital step toward a greener and more sustainable carpet industry.

The adoption of mono-material designs serves as a transformative solution to the long-standing challenges of textile recycling. By utilizing a single polymer family for both the face fiber and the backing system, this approach eliminates the need for complex and energy-intensive separation processes. In traditional carpet recycling, separating different chemical layers is often technically difficult and costly, which frequently leads to material loss. However, mono-material structures allow the entire product to be processed in a single recycling stream, significantly increasing the efficiency and quality of the recovered material. Consequently, prioritizing material homogeneity not only simplifies the recycling infrastructure but also ensures a more effective closed-loop system for the global carpet industry (Bozkurt et al., 2025, Üzümcü & Sarı, 2025).

4. INDUSTRIAL SIGNIFICANCE AND PRODUCTION DYNAMICS OF CARPETS

The textile industry constitutes a fundamental interface where global ecological integrity and industrial economics interact. Historically characterized by an intensive reliance on natural capital and high energy consumption, the sector is currently undergoing a strategic transition toward circular economic paradigms to diminish the present extensive environmental footprint. This transtition is not only an ecological necessity but also a fundamental requirement for long-term economic balance. Within this industrial context, the carpet manufacturing sector emerges as a particularly resource-intensive segment, significantly amplifying the textile industry's environmental and economic impact. Characterized by high consumption of synthetic polymers, intensive thermal energy requirements for finishing processes, and the generation of voluminous post-consumer waste, the carpet industry represents a critical area for circular intervention. The structural complexity of traditional carpets, which often integrate heterogeneous materials, poses unique challenges to material recovery and systemic sustainability. Consequently, implementing closed-loop manufacturing and eco-design principles within this sector is essential not only to mitigate its carbon footprint but also to realize the economic potential of high-value secondary raw materials, thereby contributing to the overall sustainability balance of the textile value chain.

Figure 4. A Classical Turkish Carpet (Url 4)

Throughout history, the carpet has functioned not merely as a utilitarian floor covering but as a sophisticated manifestation of cultural identity, aesthetic philosophy, and technical craftsmanship. The significance of the carpet in human life extends beyond its basic utility as a floor covering, serving as a vital bridge between domestic comfort, cultural heritage, and the technical evolution of the global textile industry. Historically, carpets have functioned as essential thermal barriers and decorative symbols of identity; however, within the modern textile manufacturing framework, they represent one of the most sophisticated applications of materials science and mass-production engineering.

As a primary segment of the home textile industry, carpet manufacturing facilitates advancements in fiber technology, chemical finishes, and structural integrity. This intersection between everyday functional requirements and industrial scale highlights the dual significance of carpet where it creates domestic environments while simultaneously serving as a major item for economic growth and the transition toward sustainable production within the textile sector.

Carpet production encompasses various engineering methodologies, primarily categorized by their structural formation techniques. These are classified into three main types: hand-made, machine-woven, and tufted carpets. Hand-made carpets are characterized by the use of natural fibers and traditional organic dyeing methods. Their structural distinctiveness stems from the application of diverse knotting techniques, which impart a unique aesthetic and physical character to each piece. Although tufted carpets involve mechanical processes, they are treated as a distinct category due to their unique needle-insertion method (Hassabo et al., 2022; Fidan et al., 2024).

Modern machine-woven carpets are complex textile structures engineered through the simultaneous interlacing of three distinct yarn systems. Unlike tufted varieties, these carpets achieve structural integrity through an integrated weaving process:

Pile System: The functional upper surface composed of warp yarns that are woven into the substrate to create the desired density, texture, and aesthetic patterns. The pile layer represents the most critical functional zone of a woven carpet, serving as both the primary interface for tactile engagement and the defining element of aesthetic character. As the structural surface in direct contact with the user, this layer dominates the comfort features of the product, durability, and decorative contribution to environment.

Architecturally, the pile layer is characterized by its versatility, allowing for the integration of diverse fiber types and varied structural configurations. In machine-woven production, these configurations are typically engineered into distinct morphologies, including:

Cut-Pile: Where the yarn loops are severed to create an upright, tufted surface known for its plush texture.

Loop-Pile: Where the yarns remain unsevered, forming continuous loops that offer superior resilience and a distinct geometric appearance.

Long-Pile: Designed with extended fiber lengths to enhance softness and provide a specific luxury aesthetic.

Warp and Weft Constituents: The structural integrity of the woven carpet, functioning as a high-performance substrate that provides dimensional stability and mechanical endurance is determined in this framework. Warp yarns primarily compose of high-tenacity polyester, polyamid, or blended yarns. Chain warps secure the weft threads in place, while stiffening warps (stuffer yarns) run straight through the fabric to provide thickness and prevent longitudinal stretching. They are mainly expected to demonstrate high tensile strength, minimal elongation under tension, and resistance to structural deformation as technical performance requirements. Weft yarns are typically made from jute, polypropylene (PP), or synthetic blends. These yarns are inserted transversely across the width of the loom to lock the pile yarns and warps together. They exhibit sufficient abrasion resistance, lateral stiffness, and compatibility with chemical sizing agents to ensure a firm bond. Constructive elements of a carpet are illustrated in Figure 6 blow.

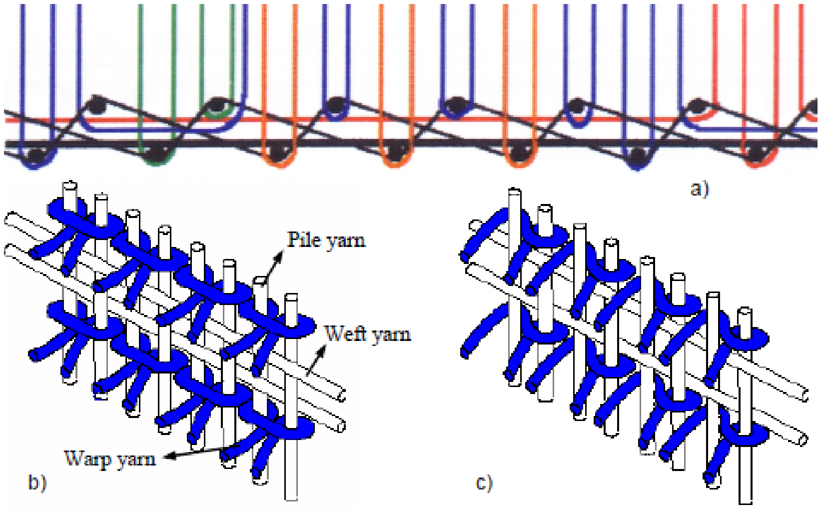

Figure 5. Constructive elements in a carpet (Topalbekiroğlu et. al, 2010)

Backing and Sizing Layer: After the weaving process, a specialized finishing or sizing agent is applied to the reverse side. This chemical treatment ensures tuft bind strength, preventing fiber shedding and enhancing the overall rigidity of the woven matrix.

4.1. Factors Contributing to the Aesthetic and Structural Degradation of Carpets

Mechanical Stress and Abrasion: High pedestrian traffic subjects fibers to repetitive compressive and frictional forces, leading to surface abrasion and the gradual loss of pile integrity.

Deformation and Matting: Under sustained loading, constituent polymers undergo viscoelastic deformation. This reduces elastic recovery, resulting in permanent matting and surface compaction.

Photodegradation: Ultraviolet (UV) exposure induces photo-oxidation and chain scission within the polymer matrix, causing color fading (chromophore degradation) and increased fiber brittleness.

Contamination and Chemical Degradation: The accumulation of particulate matter and pollutants, combined with residual surfactants, triggers chemical reactions that diminish fiber luster and molecular stability.

Hygrothermal Instability: Fluctuations in humidity and temperature compromise the dimensional stability of the textile, leading to fiber swelling or structural distortion.

Given the significant environmental impact of carpet waste, recycling is the primary strategy for circular transition of the industry. This process follows two main pathways: closed-loop recovery and open-loop repurposing.

In closed-loop systems, high-performance polymers particularly Nylon 6, are processed to maintain their molecular integrity, enabling their reuse in new high-quality fibers. In contrast, open-loop recycling diverts diverse synthetic fibers into secondary applications, such as acoustic insulation, underlayment padding, and reinforced thermoplastics.

Transition from landfill disposal to integrated recycling streams minimizes material loss and ecological footprint. Furthermore, recovering post-consumer carpets enhances resource security by providing high-quality secondary raw materials. Ultimately, these circular models demonstrate that ecological sustainability and economic viability are compatible, transforming waste management into a value-generating process.

The primary obstacle in recycling post-consumer carpets is their complex composite structure, which integrates multiple incompatible materials that are difficult to separate. While techniques such as polymer melting or supercritical CO2 precipitation exist, they often fail to balance cost-effectiveness with industrial scalability. Consequently, landfilling and incineration remain the dominant end-of-life routes.

However, driven by increasing sustainability awareness, the industry is shifting toward mono-material design to facilitate a more efficient circular economy. By engineering carpets from a single polymer family (mono material structure), manufacturers eliminate the need for complex seperation processes prior to recycling the post consumer carpet waste. This transition ensures higher purity in recovered streams, significantly improves recycling rates, and transforms carpets into a more viable resource for continuous industrial cycles.

Material recovery processes are divided into four levels, determined by the preservation of resource quality and their alignment with circular economy frameworks:

Primary Recycling (Direct Valorization): This level represents the highest step of resource efficiency, where post-consumer products are restored to their original functional state with minimal intervention. In the floor covering sector, the refurbishment and reinstallation of industrial carpet tiles serve as a benchmark for preserving structural integrity and reducing the demand for virgin inputs.

Secondary Recycling (Mechanical and Material Transformation): This phase involves the physical or chemical reconfiguration of waste into secondary applications. An example is the conversion of heterogeneous textile flooring waste into polymer melts, which are subsequently integrated into thermoplastic composites, thereby diverting material from terminal waste streams.

Tertiary Recycling (Chemical Feedstock Recovery): This advanced process involves the depolymerization of plastic waste into its constituent monomers or high-purity chemical precursors. The thermochemical recovery of caprolactam from Nylon 6 is a critical example, providing a high-quality secondary feedstock that can substitute for virgin polymers in high-performance manufacturing cycles.

Quaternary Recycling (Thermal Energy Recovery): This final stage involves the incineration of non-recyclable fractions to harness their latent calorific value. This method captures energy from residual materials that have reached their functional end-of-life, effectively acting as a final recovery safeguard (Mu et al.,2024; Salazar et al., 2024; Chaudhari et al., 2025; Lave et al., 1998).

4.2. Carpet Waste Valorization in Different Application Fields

The rapid growth of the textile industry has led to a significant increase in carpet waste, which poses a major environmental challenge due to its non-biodegradable nature. Traditional disposal methods, such as landfilling and incineration, are becoming less sustainable, driving the need for innovative valorization strategies. Repurposing these waste fibers into acoustic materials offers a promising solution within the circular economy framework. Because carpet fibers possess inherent fibrous structures, they are effective at absorbing sound and reducing noise pollution. By converting carpet waste into high-performance acoustic panels, for acoustic insulation in wheel well liners, headliners, and floor damping mats researchers can simultaneously address environmental waste management and the rising demand for sustainable building materials (Davarpanah et al., 2026; Pan et al., 2016). Additionally, the valorization of carpet waste through the development of composite materials presents a viable path toward a circular economy. By integrating reclaimed carpet fibers as reinforcements within a polymer matrix, it is possible to produce lightweight and durable composites with enhanced mechanical properties (Maheshwari et al., 2025; Pan et al., 2016; Sotayo et al., 2018; Azarfam et al., 2024; Jaiswal et al., 2021; Abbas et al., 2025; Tran et al., 2022). Integrating shredded carpet fibers as a discrete reinforcement phase provides a combining advantage; it significantly decreases environmental burdens by diverting post-consumer waste from landfills while simultaneously optimizing the structural integrity and mechanical durability of the cementitious matrix for construction applications (Simon et al., 2023; Tran et al., 2022; Gamage et al., 2024; Roshania et al., 2025; Mohammadhosseini & Yatim, 2017; Alabduljabbar et al., 2021; Idrees et al., 2023). The automotive sector utilizes recycled carpet components to achieve vehicle weight reduction and enhance acoustic performance through advanced polymer science. Recycled nylon resins (e.g., PA6) exhibit high thermal stability and mechanical strength. These are reprocessed into engine covers, radiator fans, and air intake manifolds, often matching the performance of virgin materials. Thermoplastic composites derived from carpet waste are used to manufacture outdoor decking, sound barriers for highways, and geotextiles for soil stabilization and erosion control (Sotayo et al., 2015; Janbooranapinij et al., 2021; Abdelwahab et al., 2022).

The valorization of carpet waste is a vital step for the flooring industry to reduce the environmental impact. By designing carpets within a mono-material framework and making them easy to disassemble, manufacturers can recover high-purity polymers more efficiently. This process allows both factory scraps and used carpets to be transformed into high-quality raw materials instead of being sent to landfills. This circular approach maximizes resource efficiency and significantly lowers the carbon footprint. Ultimately, turning carpet waste into valuable products helps the textile industry operate in harmony with nature while meeting sustainability goals.

5. RESULTS

The global carpet industry has undergone a significant transformation, where traditional success factors like pricing and quality are now being enhanced by advanced digital integration. By adopting innovative technologies, manufacturers have optimized their production cycles and supply chain management, leading to much more efficient operations. In this highly competitive market, the future of growth lies at the intersection of technological intervention and sustainability. Industry leaders are increasingly focusing on the production of high-quality, recyclable carpets to meet both economic and ecological demands.

Innovation is also creating entirely new market segments through functional features. The introduction of antimicrobial and anti-allergic technologies, alongside LED-embedded designs, has provided fresh momentum to the industry. Furthermore, the development of "smart carpets" represents a major leap forward; by using integrated sensors and optical fiber networks, these products can track walking patterns to detect falls or identify environmental threats like fires. This shift changes the role of a carpet from a simple floor covering to an active, functional part of a smart building.

For major global players like Türkiye, the key to long-term success involves a dual approach. Growth will depend on combining large-scale industrial investments with the artistic value of traditional, design-driven rugs. By focusing on smart materials and sustainable manufacturing, the industry can differentiate itself and secure its position in the global market. Ultimately, embracing these technical and ecological innovations is not just a choice, but a strategic necessity to ensure long-term competitiveness and resilience.

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ACADEMIC DISCUSSIONS IN THE FIELD OF TEXTILE SCIENCE AND ENGINEERING

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