Advancing Sportswear Performance through Cutinase Enzymatic Surface Modification of Polyester Knitted Fabric

BY

Endalkachew Debebe[1*], Baye B. Yilma[1]

[1]Dire Dawa Institute of Technology, Dire Dawa University, School of Textile and Fashion Design, Department of Textile Engineering, 1362 Dire Dawa, Ethiopia
[2]Ethiopian Institute of Textile and Fashion Technology, Department of Textile Chemical Process Engineering, Bahir Dar University, Bahir Dar, Ethiopia
[1*]Corresponding author: Email: endalk7upplus5@yahoo.com

ABSTRACT

This study investigates the thermo-physiological comfort properties of enzymatically modified knitted fabrics for sportswear. The cutinase enzymatically modified single jersey knitted fabric was made from 100% PET. And also, for enzymatic surface modification, Suson manufactured cutinase enzyme was used. Box-Behnken design was used as a statistical tool for investigating the effect of cutinase concentration and other factors. Thermo-physiological comfort properties of knitted fabric such as thermal conductivity, thermal resistance, fabric wettability, tensile strength, and fabric stiffness, weight-loss, pilling resistance of the treated and untreated fabric were tested and analyzed. The enzymatic treatment and structurally modified designed fabrics significantly enhances comfort property of knitted fabrics. SEM analysis shows slight surface morphological changes, while FTIR results indicate the introduction of new hydroxyl and carboxyl groups, suggesting improved surface hydrophilicity. Additionally, the tensile strength (0.27%) and weight loss (0.26%) are remained nearly unchanged by cutinase hydrolysis-treated polyester fabric. According to the fit statistics, the R2 values of air permeability, wickability, thermal conductivity, and resistance are 98.24%, 98.78%, 99.55%, and 99.11%, respectively. These findings demonstrate the potential of cutinase enzymatically modified knitted fabrics to improve the overall comfort properties and performance of sportswear, offering a promising approach for developing advanced functional textiles.

Keywords: Cutinase, Thermo physiological Comfort, Sportwear, knitted

1. INTRODUCTION

Sportswear's thermo-physiological comfort has made it a popular clothing type all over the world (Nasrin *et al.*, 2023). Sportswear's practical purpose and consistent appearance that distinguished one sport from another led to its separation from general fashion design in the early 1900s. And also, sportswear has significantly influenced fashion trends and textile innovation over the last fifty years or more (Bielefeldt Bruun and Langkjær, 2016). Furthermore, high-active sports textile is a very difficult field to work in in the current period of growth because it needs to be both useful and comfortable (Ahmad *et al.*, 2023). With the latest developments in textile technology and global shifts in design and clothing, consumers now base their decisions not just on the fabric's appearance but also on its level of comfort (Agarwal et al., 2021b; Choudhury et al., 2011a). Therefore, the textile industries have focused their efforts on applying cutting-edge technology and functional materials to redefine the notion of clothing (Yetisen *et al.*, 2016). To provide the best possible comfort and performance for sportswear textiles, there are certain specific demands which should be met (Atalie, , Pavla Tesinova, Melkie Getnet Tadesse, , Eyasu Ferede, Ionut and and Emil Loghin, 2021). Some of the features that are necessary are the ability to manage dampness, dry off rapidly, maintain the heat of the body, control temperature, and permit permeation of air (Govindachetty, Sidhan and Venkatraman, 2014). And, the performance of sportswear fabrics is influenced by the type of fiber selected, the nature of the blending, the structure of the yarn and fabric, and the finishing treatment (Özdil, Marmarali and Kretzschmar, 2007). PET is the most widely used material for sportswear. However, the comfort properties of polyester (PET) fabric can be a challenge. It is because of the hydrophobic properties of PET bring, static accumulation, low moisture absorption capacity, and makes it poor comfort and aesthetic characteristics (Kumar & Senthil, 2020). And also, the PET has a low thermal conductivity, low thermal absorptivity, and low heat flow, but it possesses higher thermal diffusivity (Mounir *et al.*, 2012). Hence, PET fabric moisture absorption and perspiration treatment is crucial and has gained great attention of textiles researchers so far. Currently, to achieve this thermo-physiological characteristics researchers focus on surface modification of PET fabrics by using different methods and techniques (Kanelli *et al.*, 2015). However, traditional methods such as use of chemicals or plasma treatment can significantly impact on mechanical properties of polymers, and also have high cost and environmental effect (Nemani *et al.*, 2018). Enzymatically treated PET fabric significantly enhances the physiological comfort characteristics of polyester materials (Newashy et al., 2019)

Therefore, focusing on enzymes as research brings a more environmentally friendly and substitute for traditional chemical processing of fabrics for surface modification purposes (Kumar and Senthil Kumar, 2020). The enzymatic hydrolysis of synthetic fibers enhances their hydrophilicity and can improve properties such as moisture regain, dye uptake, and shear properties (Tegegne and Haile, 2024). Specifically, cutinase and lipases are extensively used in industrial applications (Ferrario *et al.*, 2016). However, studies on hydrolysis of PET with cutinase are very limited. The aim of this research was to investigate the thermo-physiological comfort properties of enzymatically modified polyester knitted fabrics for sportswear applications. In this study, the cutinase enzyme hydrolysis technique was applied, to analyze the thermo-physiological comfort properties of PET fabric. Furthermore, each test parameter has been optimized using a box-behnken design.

2. LITRATURE REVIEW

2.2 CLOTHING COMFORT PROPERTY

Textile-based sportswear should have certain basic qualities, such as being anti-static, antibacterial, breathable, robust, and flexible (Scataglini et al., 2020). It ought to quickly absorb moisture to help keep the skin dry and quickly remove perspiration from the skin (Islam et al., 2023). The feeling which is experienced as comfortable when putting on clothes is something that everyone identifies with; this is ignited by different causes subjectively (Turukmane & Daberao, 2023). Through understanding the textile physiology mechanism of sportswear is the bridge that links the human body to the dress giving an account of the physiological properties of the textile (Uttam, 2013). For sportswear, there are two main categories of textile/clothing comfort that are crucial; Psychological comfort and Physical comfort (tactile, thermal, ergonomic).

Thermo-physiological/ thermal comfort: Athletes' thermal equilibrium is vital when performing any kind of sporting exercise. In this case, it is evident that the wearer's body loses heat at a pace that is always equal to the rate at which heat is produced by the various physiological processes. This action always helps determine a fabric's capacity to regulate moisture and breathe in sports textiles (Khalil, Těšinová and Aboalasaad, 2022). Therefore, breathability and an item of clothing's overall moisture management capacity can be used to determine thermo-physiological comfort.

2.2 SURFACE MODIFICATION OF FIBER

2.4 Surface Modification of Fibers

Synthetic fibers have relatively high levels of orientation and crystallinity that impart the desirable properties; they contribute to their structural resistance to coloration by dye compounds and finishing with various materials. Different methods are employed to enhance modification of these fibers. In this sense, a great many studies have been carried out, including: physical methods; corona discharge (Yang *et al.*, 2010) , plasma (Dave *et al.*, 2013), laser, electron beam and neutron irradiations functionalization (Getnet and Chavan, 2015) and chemical methods; enzymatic modification grafting of different monomer (Kanelli *et al.*, 2015), application of supercritical carbon dioxide, sol-gel technique, layer-by-layer deposition and treatment with different reagents (Parvinzadeh, 2012). In last decades, some of previous methods used to modify usually consumed a lot of energy and water, higher manufacturing costs; a negative effect on some of the bulk properties of fibers; they may create harsh conditions; they produce undesirable side effects and ⁄or waste disposal problems; there is more waste and the process is highly odorous for workers. Recent methods are modified with new technologies to improve their efficiency (Ebrahimi *et al.*, 2011)

Enzymatic hydrolysis: To avoid the use of chemical catalysts and to achieve decomposition at milder conditions, therefore reducing operational costs and avoiding harsh and polluting chemicals, enzymatic hydrolysis of PET will has been the object of preliminary research (Di Bisceglie *et al.*, 2022). Cutinases belong to the α/β hydrolase superfamily. This class of enzymes is known to be able to hydrolyze high-molecular-weight synthetic polyesters such as poly (butylene succinate) (PBS) (Chen *et al.*, 2013), poly(1,4-butylene 2,5-furandicarboxylate) (PBF) (Gigli *et al.*, 2019), poly(ethylene 2,5-furanoate) (PEF) (Weinberger *et al.*, 2017), and poly(ethylene terephthalate) (PET) (Quartinello *et al.*, 2017). Moreover, cutinases can catalyze esterification and trans-esterification reactions on both small substrates and polymers (Gross, Ganesh and Lu, 2010; Maurya, Bhattacharya and Khare, 2020), therefore showing a wide range of applications in the environmental, chemical, detergent and textile industries. Cutinases can be distinguished from esterases by their ability to hydrolyze high-molecular-weight polyesters. Moreover, cutinases can act as promising stereo selective catalysts in esterification and trans-esterification reactions and present better selectivity than lipases (Liang and Zou, 2022).

Catalytic mechanism of cutinases for PET hydrolysis: PET is a polymer composed of terephthalic acid (TPA) and ethylene glycol (Martínez and Maicas, 2021). Cutinases from various organisms, such as Thermobifida halotoleran (Ribitsch *et al.*, 2012), F. solani pisi (Silva *et al.*, 2005), Fusarium oxysporum (Kanelli *et al.*, 2015), T. fusca (Oeser *et al.*, 2010), and Thermobifida cellulosilytica (Ribitsch *et al.*, 2015), can hydrolyze the ester bonds found on the surface of PET fibers, thus improving their hydrophilicity without compromising the integrity of the material (Silva *et al.*, 2005).

3. METHODOLOGY

In this study, 100% polyester yarn containing 120 D single jersey knitted fabric, with the detailed fabric properties shown in table 1 were used. And, for enzymatic modification, cutinase enzyme (manufactured by Sunson, China) for hydrolysis; dimethyl sulfoxide (DMSO) to solubilize and swell up polyester for accessibility of the enzyme to the substrate; and di-hydrogen phosphate ions (H2PO4-) with a pH range of 6.0–8.0 as a buffering agent were used.

Surface modification of fabric

Before enzymatic treatment, the polyester knitted fabric samples were washed and scoured to remove any dirt and other materials. The scouring was carried out with 5% Lissapol (C68H136O21**,** 99% pure nonionic wetting agent, which was gotten from Imperial Chemical Industries in Britain) at 100 ^{o}C for one hour (Gupta et al., 2007). For all experiments, deionized water was used. The fabric samples were rinsed, dried, and conditioned before further treatment at a relative humidity of 65 ± 2% and a temperature of 20 ± 2°C for 24 h.

Enzymatic treatment of PET fabric was performed by cutinase enzyme. The concentration of enzyme was 2.5%, 5% and 7.5% o.w.f in single usage, and also enzymatic process was conducted at 40 ^{o}C, 50 ^{o}C, and 60 ^{o}C for 30 min, 50 min, and 65 min at pH 8. The 17 experimental runs were designed using Box-Behnken Design (BBD). The alkalinities of the solution used in the enzymatic process were adjusted with phosphate buffer. Knitted sample fabric was treated with cutinase enzyme at 40 rpm using MESDAN auto wash machine. Deactivation of enzyme was carried out by keeping the fabrics at 100 °C for 10 min after enzymatic treatment (Toprak and Anis, 2020). After inactivation, the samples were soaked in ethanol for 5 min to remove sorbed enzyme if any. This was followed by soaping with 5 g/L Lissapol N at 40°C with a liquor ratio of 1:50 (Gupta, Chaudhary and Gupta, 2015).

Characterization of the produced knitted fabric samples: The fabrics were tested to evaluate the characteristics of knitted fabrics such as fabric weight (ISO 3801 Metler brand digital balance), fabric thickness (ASTM D1777-96 digital thickness gauge), fabric stiffness (ASTM D4032), extensibility (ASTM D2594), tensile strength (ASTM D5034 textile grabbed method), pilling (ASTM D4970 ICI pillbox method), air permeability (ASTM D737), thermal conductivity and resistance (ASTM D1518) and vertical wicking (AATCC standard test method 79–1992).

Tests and Assessments:

All samples were prepared by preconditioning at standard atmospheric [temperature], unless otherwise noted. (65±5) % for relative humidity; (20±2) °C/ (68±4) °F following ASTM D1776's instructions with a conditioning cabinet.

The fabric weight (GSM) test was measured by a Metler brand digital measuring balance in compliance with ISO 3801. Add the fabric weight (GSM) was recorded.

The thickness of the fabric samples was also measured using a digital thickness gauge (MESDAN, model D-2000) at 100 KPa with ASTM D1777-96.

Fabric stiffness was measured by a pneumatic fabric stiffness tester 3396 to assess the stiffness of the cloth in accordance with ASTM D4032.

Extensibility of the fabric was tested with an Extensometer using 75 mm by 85 mm size of the specimens, in accordance with ASTMD2594.

Tensile strength test was measured according to the ASTM D-5034-textile grab test method using Tensolab 100 (Mesdan Lab, Italy).

Pilling resistance, the fabric sample was wrapped around rubber tubes, facing outward, and placed into revolving boxes lined with cork. Finally, the results compared to a scale of one to five, with five denoting no pilling and one denoting severe pilling, to photographic standards and were followed the ASTM D4970 protocol.

Air permeability of the fabrics was measured on SDL atlas tester. All fabrics were preconditioned for 24 hours at 20 ± 2 °C and 65 ± 2 % relative humidity in a conditioning room. Measurements were performed by application under 100 Pa air pressure per 20 cm^2 fabric surface. Averages of measurements from 10 different areas of fabrics were calculated. Results were expressed as ($cm^3/cm^2/s$).

In addition, thermal conductivity and resistance of the polyester knitted fabric was measured with HAMBURG WL 372 apparatus. Thermal conductivity of the fabric was computed using the following equation (1).

$$K = \frac{Q * L}{A * \Delta T} \quad (1)$$

Where, K is thermal conductivity (W/m.k), Q is heat transfer per unit time (M), L is thickness of the fabric (m), A is cross-sectional area through which heat is transfer (m^2), ΔT = Temperature difference across the fabric (k). The thermal resistance of the fabrics was assessed by applying the following equation (2).

$$R = \frac{L}{A * k} \quad (2)$$

Where, R is thermal resistance (K/W), K is thermal conductivity (W/m.k), L is thickness of the fabric (m), A is cross-sectional area through which heat is transfer (m^2). So far, the wickability of polyester fabric was evaluated using vertical wicking with capillary rise method, AATCC 197 is one of the standard methods. A 20 cm × 2 cm stripped fabric was taken and one end was immersed into water reservoir for five minutes for capillary action. The wicking height was measured in lengthwise.

FTIR analysis: JASCO FTIR (Perkin Elmer FTIR)/6600 was used to assess the surface chemistry of control and enzymatically modified polyester fabrics under ASTM 7575 testing procedures. The data was recorded in the spectrum of 4000-400 cm^{-1} frequency band.

SEM analysis: the Scanning Electron Microscope (SEM) was used for an examination of fabrics' surface morphology, fiber structure and treatments applied to the fabric.

Weight loss analysis: to assess the effect of cutinase surface modification and was performed using an electronic balance (Sartorius-GD 503). The samples were dried in an oven at 105 °C for 90 min and weight in a closed weighing bottle after cooling using equation three.

$$\text{Weight loss \%} = \frac{(W_1 - W_2)}{W_1} * 100\% \quad (3)$$

Where, W_1 and W_2 are the dry weights of the fabrics before and after enzyme treatment, respectively.

Table 1: property of single jersey knitted fabric

Fabric sample code	Loop length (mm)	Course per cm	Wale per cm	Stitch Density cpc*wpc	Loop Shape Factor cpc/wpc	Thickness (mm)	Fabric weight (g/m^2)
S1	2.8	19	14	266	1.34	0.35	76

4. RESULT AND DISCUSSION

4.1 ANALYSIS OF PET SURFACE MORPHOLOGY

FTIR analysis of cutinase treated PET: When cutinase broke down ester bonds on hydrolyzed polyethylene terephthalate (PET), the polymer undergoes surface changes. Consequently, carboxyl and hydroxyl groups were formed. Thereafter, new bands of absorption appeared coupled with the transformation of old ones, thus changing the FTIR spectra of PET. According to the result shows in figure 1, when ester bonds broke down, they form carboxylate anions. This was seen by identifying certain absorption bands on 1551 cm^{-1} (–1580-1550 cm^{-1}) and 1410-1350cm^{-1} for asymmetric stretching associated with the carboxyl group and symmetric stretching (Dave *et al.*, 2013). When hydrolyzed, alcohol groups produced broad absorptions that could been attributed to free hydroxyl groups at 3444cm^{-1}, which is between 3500 to 3200 cm^{-1} (Tegegne and Haile, 2024). And there were still ester groups that had not been hydrolyzed, we would expect that the characteristic C=O stretching peak at 1715cm^{-1} would still been visible, only that its intensity had been less than when no hydrolysis had taken placed entirely. The new C–O stretching peaks 1087 cm^{-1} which is within the range of 1100-1050 cm^{-1} as well as O–H bending ones on 1349 cm^{-1} within the range of 1400-1300 cm^{-1} either emerged or intensified, what signifies the production of hydroxyl terminus entities through enzyme catalysis (Kanelli *et al.*, 2015).

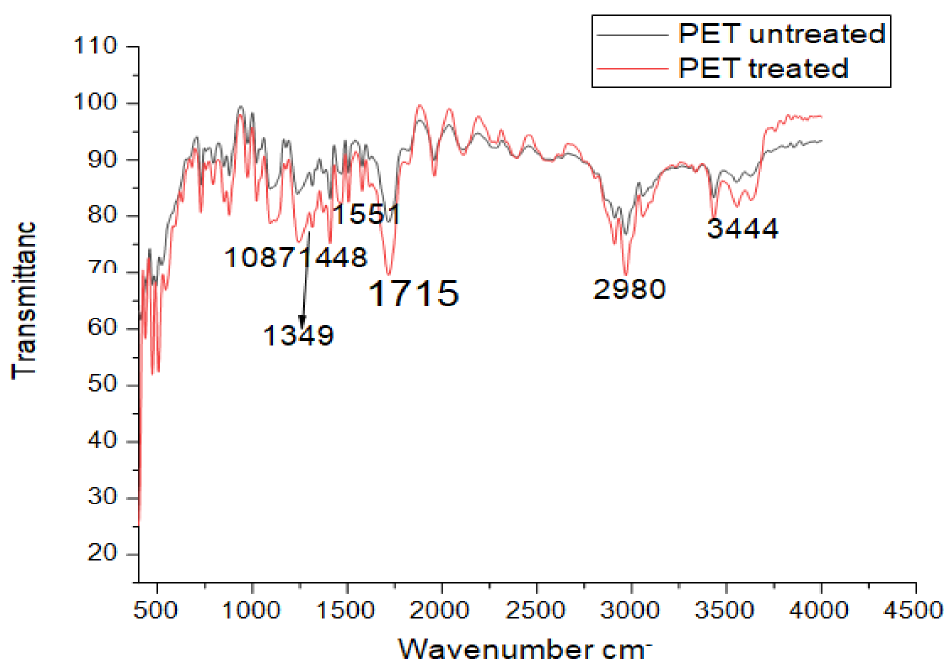
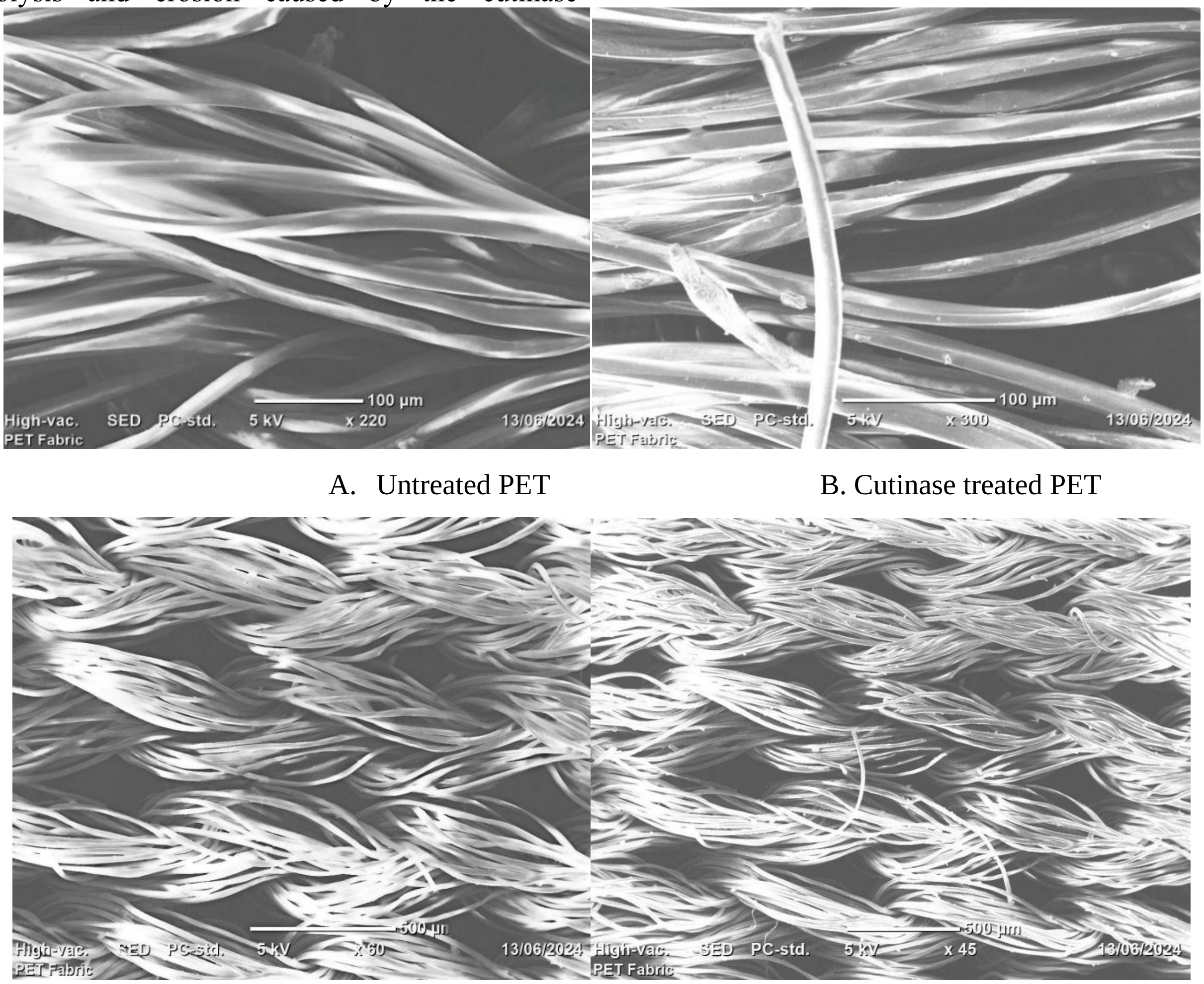


Figure 1. FTIR result of PET Cutinase treated and untreated fabric

SEM analysis of cutinase treated PET fabric: After the PET fabric was treated with cutinase enzyme and enzymatic hydrolysis was performed, the scanning electron microscope (SEM) analysis showed a slight modification of the fabric surface in comparison with its initial state before treatment. According to figure 2, the SEM images of untreated PET fabric typically show smooth, uniform fibers with no significant surface irregularities. However, the treated PET SEM images show slight changes such as increased roughness, small pits, and irregularities on the fiber surface. These changes indicate the localized hydrolysis and erosion caused by the cutinase enzyme. The enzyme treatment did not induce any detectable change of surface morphology of the PET substrate (Donelli et al., 2009).



A. Untreated PET B. Cutinase treated PET

C. Untreated PET D. Cutinase treated PET

Figure 2. SEM micrographs of cutinase treated and untreated pet fabrics.

Wight loss analysis of cutinase treated PET fabric: Many factors, such as the concentration of cutinase, treatment duration, and treatment temperature, could have caused the low degree of weight loss (0.26%) of polyester fabric treated with cutinase. Because the amount of cutinase available is low, the polymers that live on surface are not degenerated in the hydrolysis of ester bonds due to minimal interaction between polyester and enzyme. This would have a great impact on surfaces degrading a little bit and as a result, reducing mass considerable weight loss of the fabric (Matsumura et al., 2008).

4.2 ANALYSIS OF PHYSICAL PROPERTY

Tensile strength analysis of cutinase treated PET fabric: Under given conditions (specific nature and extent of hydrolysis process, such as cutinase concentration, treated time, temperature), the tensile strength is not significantly changed by cutinase hydrolysis treated polyester fabric as shown in table 2.

At a low concentration of cutinase, the effect of hydrolysis is limited to the surface of the fabric so that the enzyme doesn't penetrate deeply to affect such bulk properties of fibers like tensile strength (Lee and Song, 2010). The primary role of cutinase is to engage with the ester linkages present on the surface, thus leading to marginal adjustments on the surface; this is without any notable loss in the tensile strength of the fiber's inner structure. Enzymatic reactions on polymers mainly begin with surface hydrolysis. If the time is short, an enzyme doesn't get the time to degrade deeper or extensively which could alter its tensile strength (Park *et al.*, 2014).

Table 2. Tensile strength and elongation % of test result cutinase treated fabric

Fabric Sample	Fabric weight (g/m^2)	Thickness (mm)	Max. Breaking force in N		Elongation % at Break	
			Length Wise	Width Wise	Length Wise	Width Wise
S_1	76	0.35	171.04	36.05	28.54	9.08
S_{1T}	75.8	0.35	170.58	35.42	27.51	9.01

PET Cutinase treated fabric on fabric stiffness: According to test result seen in figure 3; fabric stiffness in both the face to face and back-to-back S_1 untreated PET has higher than treated PET (S_T). Hence, the PET polymer chains are partially broken down by lipases and cutinases, which causes hydroxyl and carboxyl groups to develop on the surface of the fabric. This makes the PET fabric more hydrophilic, which increases its flexibility and decreases its stiffness (Matsumura *et al.*, 2008). After enzymatic hydrolysis, the PET polymer's tight packing and crystalline structure are disrupted, which results in a decrease in fabric stiffness and as a result the longer polymer chains are broken down by the enzymes, which reduce their length and intermolecular interactions and improves the fabric's softness and flexibility (Kumar and Senthil Kumar, 2020).

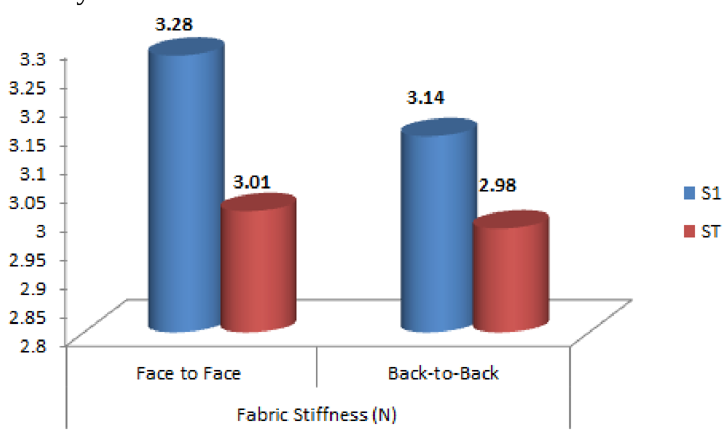


Figure 3. Pneumatic Fabric Stiffness test result of treated PET

Fabric extension and recovery cutinase treated PET*:* As a result of polymer chain breaks, decreased crystallinity, and surface modification, enzymatic hydrolysis of PET fabric changes the fabric's recovery and extension. According to the extension recovery test result in table 3 enzymatic treated PET have higher extendibility and lower recovery. The deterioration of the material's structural integrity causes these modifications, which normally lead to greater fabric extension (more flexible) and decreased fabric recovery (less able to return to original shape) (Vertommen *et al.*, 2005). PET may be efficiently hydrolyzed by enzymes to form its monomers, which reduces the durability of the fabric and modifies its mechanical characteristics, such as recovery and extension.

Table 3: Cutinase treated PET extension and recovery result.

Extension and Recovery (%)

		S_1	S_T
Extensibility (%)	Length wise	51.4	54.8
	Width wise	94.5	97.2
Recovery (%)	Length wise	31.2	28.4
	Width wise	68.1	59.2

Pilling property of cutinase treated PET fabric: According to the test result in table 4 the susceptibility to pilling of treated sample is lower than the untreated one. Hence, through the breakdown of the polymer chains, the enzymatic action might weaken the fibers. Cutinase hydrolysis mostly breaks down the ester linkages in PET, changing the surface of the fabric and the polymer chains. Increased fibrillation, or the splitting of fibers into smaller fibrils, may result from this surface modification, which may promote the development of pills. Reduced pilling resistance results from weaker fibers' propensity to break and form pills in response to mechanical stress (Lee and Song, 2010).

Table 4. Pilling resistance of cutinase treated PET knitted fabric

Sample Fabric	Susceptibility to pilling
S_1	4-5
S_T	3-4

4.3 ANALYSIS OF THERMO-PHYSIOLOGICAL COMFORT PROPERTIES

Thermo-physiological comfort refers to the wearer's perception of comfort influenced by the thermal and moisture transfer properties of a fabric. It is a critical factor in the design and selection of textiles, especially for garments meant for sports, outdoor activities, and protective clothing. Analyzing thermo-physiological comfort involves evaluating several key properties of the fabric as presented in the Table 5 below.

Table 5. Experimental runs and average test results for each response.

		Factor 1	**Factor 2**	**Factor 3**	**Response 1**	**Response 2**	**Response 3**	**Response 4**
Std	Run	A:Cutinase Concentration	B:temperature	C:time	Air permeability	Thermal conductivity	Thermal Resistance	Wettability (capillary rise)
		%	^{0}C	min	(cm^3/cm^2/s)	(W/mK)	(m^2.K/W)	cm
8	1	7.5	50	65	210	0.15	2.97	3.2
5	2	2.5	50	35	185	0.28	1.59	1.5
14	3	5	50	50	200	0.21	2.12	2.2
4	4	7.5	60	50	208	0.16	2.78	2.9
3	5	2.5	60	50	200	0.21	2.12	2.4
2	6	7.5	40	50	201	0.19	2.34	2.5
16	7	5	50	50	199	0.2	2.23	2.2
11	8	5	40	65	206	0.17	2.62	2.8
7	9	2.5	50	65	203	0.19	2.34	2.6
6	10	7.5	50	35	205	0.18	2.47	2.7
1	11	2.5	40	50	190	0.27	1.65	1.7
17	12	5	50	50	198	0.21	2.12	2.1
13	13	5	50	50	200	0.21	2.12	2.2
15	14	5	50	50	199	0.21	2.12	2.1
9	15	5	40	35	191	0.26	1.71	1.8

12	16	5	60	65	209	0.15	2.97	3.1
10	17	5	60	35	201	0.19	2.34	2.5

Table **6**. ANOVA analysis of thermo-physiological comfort properties of treated fabric. [a]Air permeability, [b]thermal conductivity, [c]thermal resistivity and [d]wickability.

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model[a]	714.73	9	79.41	43.43	< 0.0001	significant
A-Cutinase Concentration	264.50	1	264.50	144.65	< 0.0001	
B-temperature	112.50	1	112.50	61.52	< 0.0001	
C-time	264.50	1	264.50	144.65	< 0.0001	
Model[b]	0.0234	9	0.0026	173.34	< 0.0001	significant
A-Cutinase Concentration	0.0091	1	0.0091	607.50	< 0.0001	
B-temperature	0.0041	1	0.0041	270.00	< 0.0001	
C-time	0.0078	1	0.0078	520.83	< 0.0001	
Model[c]	0.0001	9	6.799E-06	415.65	< 0.0001	significant
A-Cutinase Concentration	0.0000	1	0.0000	1392.74	< 0.0001	
B-temperature	0.0000	1	0.0000	619.00	< 0.0001	
C-time	0.0000	1	0.0000	1194.05	< 0.0001	
Model[d]	3.60	9	0.4000	62.92	< 0.0001	significant
A-Cutinase Concentration	1.20	1	1.20	188.96	< 0.0001	
B-temperature	0.5512	1	0.5512	86.71	< 0.0001	
C-time	1.28	1	1.28	201.35	< 0.0001	

Analysis of air permeability:

According to the data of table 5 and ANOVA analysis of Table 6, the air-permeability of fabric samples is significantly changed as of 0.0001 ($P<0.005$) confirmed. So far, according to the fit statistics, the R^2 value is 0.9824. And also, Figure 4 shows that the concentration of cutinase, temperature and time has a considerable impact on the air permeability of the fabric. The cutinase treatment alters the PET fabrics' surface by cleaving ester bonds at the surface of the fabric. Consequently, the fabric's structure and surface properties are altered through this enzymatic action. The treatment temperature increases the air-permeability of the fabric also increase. The effect on PET's physical and chemical properties by temperature along with its interaction with other treatment variables. Moreover, when treatment time increases the air-permeability of the fabric also increase. This is due to the fact that the amount and the type of changes in either chemical or physical properties of these fabrics depend on how long they have been processed. This is also coincided with other study that extended period of time led to increased surface hydrolysis, porosity and air permeability. For instance, if an enzyme is allowed to react with the material for too long it could lose too many mechanical properties due to excessive water attack (Gamerith et al., 2017). High-air permeability in fabrics enhances air circulation, reducing their insulating property. As material air permeability increases, so does the lower in its thermal insulation values.

Based on the experimental analysis, the following regression equation is derived:

$$\text{Air permeability}=199.2+5.75A+3.75B+5.75C-3.25AC-1.75BC+1.78C^2 \quad (4)$$

According to the model, the air permeability of the fabric is affected by cutinase concentration, temperature and time. All main effects show that there is direct relationship where each factor contributes positively towards the air permeability when it is viewed, separately. However, analysis of cutinase concentration against time (−3.25AC) indicates that air permeability increases independently but together they do not enhance it. Temperature and time interact in a similar manner (−1.75BC) suggesting that simultaneous high levels of both factors could have troublous effect.

Analysis of thermal conductivity:

In the table 5, the fabric samples exhibited the values of thermal conductivity for each experimental run. In Table 6 also Modelb, the significant value of thermal conductivity is calculated (0.0001). So far, Figure 8 depicted the effect of the independent variables (cutinase enzyme concentration, temperature, and time) on thermal conductivity. The value of R^2 for thermal conductivity is 0.9955. There is an indication that almost all variations noticed in thermal conduction are due to cutinase concentration, temperature and time factors. A fabric's thermal conductivity determines its efficiency in handling heat transfer. Fabrics with high thermal conductivity help in transferring heat faster, leading to a cooler feeling. In contrast, materials with low thermal conductivity tend to trap the heat thereby maintaining warmth. The thermal comfort in dressing depends on thermal conductivity (Leabeater, James and Driller, 2022). Thus, heat flow control in garments enhances wearing comfort to the natural environmental condition.

The surface characteristics of PET fibers, like cutinase, areknown to undergo enzyme treatments that involve breaking down the surface of the fiber to modify their surface properties as well as change their inside structure, and this has an impact on heat transfer (Nasrin et al., 2023b). The enzyme breaks ester bonds on fiber surface so that it can release microfibers that will create more surface roughness that trap most of the air reducing the thermal conductivity as revealed in Figure 4. As the cutinase concentrations increase, this leads to more extensive hydrolysis thereby bringing about additional changes in the fabric's surface. This could also lead to increased changes in fabric's porosity or structure lowering its heat conductivity. (Ferrario et al., 2016) found that when there are a larger number of enzymes present it causes greater changes in fibrous structures which allow for better moisture transport leading to reduced thermal conductivity making fabrics more comfortable.

According to Figure 4, when temperature increased thermal conductivity of the fabric decreased. The temperature plays a key part in enzyme action by influencing how fast biochemical reactions happen at fabric surface (Kyzymchuk et al., 2023). The study found out that up to a certain peak point, enzyme action kept rising as temperatures increased before starting to down while promoting polyester hydrolysis in fibrous materials. It is also necessary to give enough time the enzyme to interact with and modify the fabric surface. An enhanced enzyme activity and its effectiveness is generally achieved after a longer treatment duration. To cite an example, the study (Nguyen et al., 2023) found out that when the process lasts longer, there is more polyester fabrics hydrolysis due to enzymes. Thus, such conditions significantly decrease thermal conductivity through creating additional micro-fibrils while enlarging a material's surface area.

The regression equation is formulated based on the experimental data as follows:

$$\text{Thermal Conductivity} = 0.2080 - 0.0338A - 0.0225B - 0.0313C + 0.0075AB + 0.0150AC + 0.0125BC - 0.0040A2 - 0.0115C2 \qquad (5)$$

Given all other things are controlled, a negative coefficient of -0.0338 in the regression equation implies that with an increase in cutinase concentration there will be a decrease in thermal conductivity. This implies that by increasing the amount of cutinase on the fabric, it can have its surface modification and potential reduction of heat flow rate through the garment. The treatment temperature is reflected by the negative coefficient of -0.0225 in terms of an inverse relationship with thermal conductivity. It is possible that increased temperatures might make other kinds of treatment (like cutinase) work well because they lead to more significant changes in the material properties. The negative value (-0.0313) for heat conductivity would mean that conduction increases when treated longer time periods are applied to the PET fabric. The coefficient of the interaction term concentration and temperature are 0.0075. The positive coefficient shows that together both the cutinase concentration and temperature raises the thermal conductivity although this interaction is not as significant as the main effects. Specifically, the positive interaction term (0.0075) suggests that the combined increase in both factors can slightly increase thermal conductivity, counteracting the main effects.

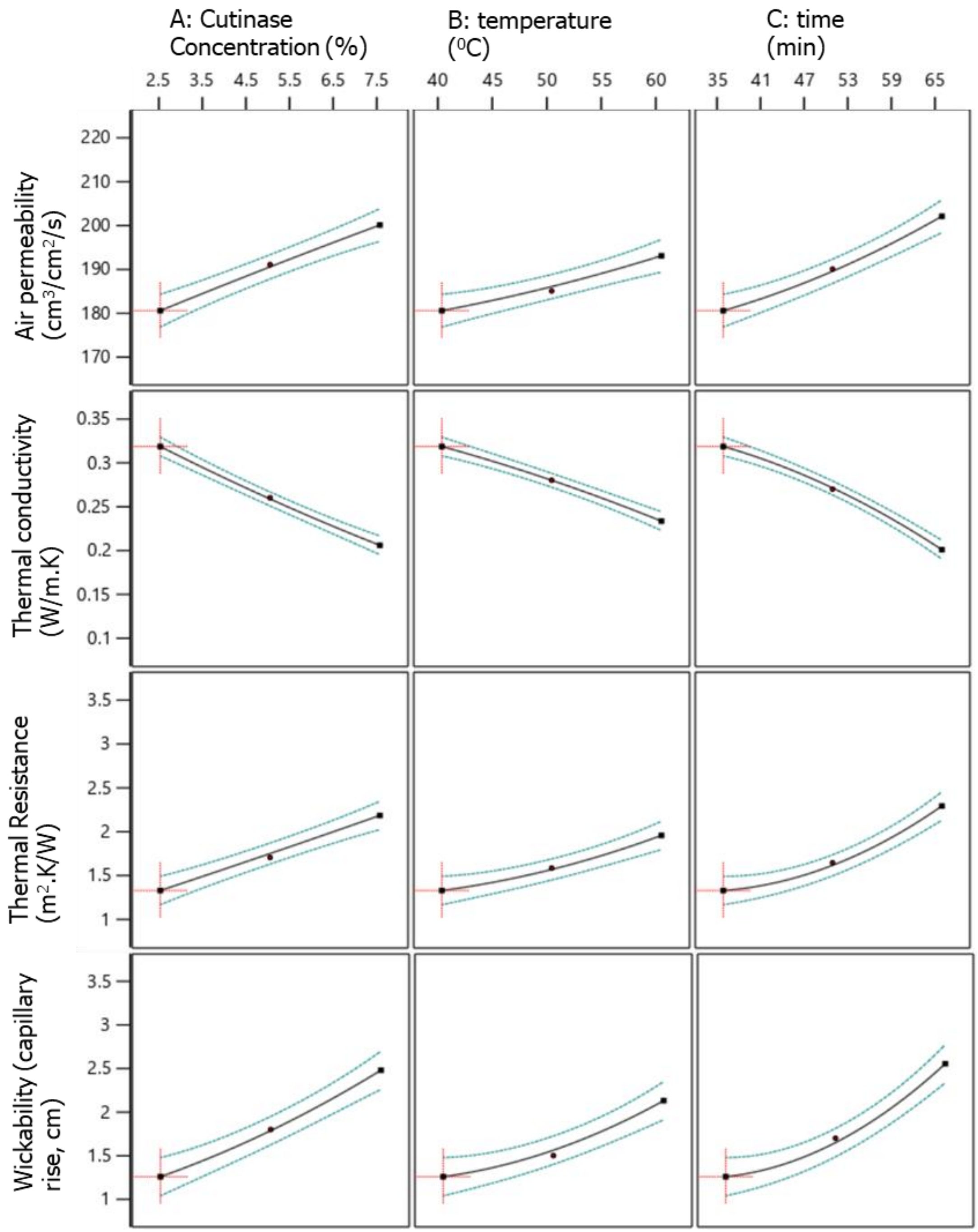


Figure 4. The effect of cutinase concentration (%), temperature (^oC) and time (min) on thermo-physiological comfort properties of PET fabric

Analysis of thermal resistance:

The fabric samples, as indicated in the table 5, had a remarkable reduction in thermal conductivity which is significant that the p-value being less than 0.05. This means that, independent variables: cutinase enzyme concentration, temperature and time are highly significant on thermo-physiological comfort property as indicated by ANOVA analysis in Table 6. The amount of variation of the dependent variable thermal resistance that can be predicted from cutinase concentration, temperature, and time is 0.9957 (R^2). This showing that 99.98% of variability in thermal resistance is accounted by model.

The regression equation for thermal resistance is given below based on the analysis.

$$\text{Thermal Resistance} = 0.0090 - 0.0017\text{A} - 0.0011\text{B} - 0.0016\text{C} + 0.0004\text{AB} + 0.0008\text{AC} + 0.0006\text{BC} + 0.0009A^2 + 0.0005C^2 \qquad (6)$$

In the regression equation of thermal resistance, one can see the relevance of cutinase concentration, temperature or growth conditions on the thermal properties of treated fabric. From the main effects, we can deduce that increase in any is associated with reduction in the thermal barrier effect; however, with respect to interaction and quadratic terms, there are indications that these propositions would obtain in a more complicated sense, ranging from easing some to worsening others. For the achievement of the thermal resistance, breathability, and general comfort balance in sportswear applications, it is crucial to understand these dynamics. This translates that a one unit increase in the cutinase concentration lowers the thermal resistance by 0.0017 units in A assuming all other conditions remain the same. It could be deduced from this statement that increased quantities of cutinase deteriorate the fabrics resistance to heat conduction because it probably enhances hydrolysis hence a looser fabric construction. An increase in temperature reduces thermal resistance by 0.0011 units per unit increase in B with a coefficient of -0.0011 for B. This leads to more modifications within the fabric material thus lowering its thermal resistance when enzyme activity increases at higher temperatures.

The consequences on thermal endurance of the degree of cutinase applied is diverse; it involves alike linear and nonlinear relationships. There is however a more complicated situation; temperature and time interaction terms along with quadratic influences depict that not every increase in cutinase concentration lessens thermal endurance. To do this, the treatment protocols need to be optimized carefully so that the material balances between thermal resistances, breathability without compromising its all-round comfort especially when it comes to sports attire or apparel. Various ways in which temperature affects thermal resistance exist; these include linear and interactive effects. Thermal resistance is typically lowered by higher temperatures, but there are complications from interactions that result from having other variables like timed cutinase concentration. Properly optimizing protocols for processing membrane models will therefore be important in striking a balance between heat ability, breathability its comfort in general. According to (Arnal *et al.*, 2023) the study, temperature is very crucial in modifying fabric properties. It also alters fabric resistance to heat. It is important to regulate temperature toward achieving particular fabric traits in enzymatic treatment techniques.

Moreover, numerous factors determine how time affects thermal conductivity, many of them being linear and nonlinear. The relationship between thermal conductivity and treatment time is predominantly inverse; however, further analyses show that this may not always be the case. The interaction between cutinase concentration, treatment temperature, treatment time and their squared values indicate that there would be significant variations. In areas such as sportswear, particularly, it is therefore important that we achieve a balance between thermal insulation, breathability and comfort when designing treatment methods. The resistance to heat decreases first, but when this takes a long time, material structures change and resistance raises. This fact was mentioned by (Weinberger *et al.*, 2017) who also added that time treatment should be regulated correctly because in case it is not some essential properties will be lost in sportswear industry.

Analysis of fabric wickability:

In thermo-physiological comfort features determination, mainly knitwear wickability is a key factor in sportswear context. Thermo-physiological comfort refers to the capacity of a fabric to handle heat and moisture to enable the wearer maintains an optimum body temperature and dry skin state during exercise. A significant change in the wickability of the fabric samples was evident from the results displayed in Table 5 with a P-value < 0.05. Heat transmission which helps in temperature control may be affected through fabrics with different wickability properties but they can still maintain heat within the range of thermo-neutral state. The human skin remains dry due to moisture-wicking fabrics that stop the chilling effect caused by wet clings on it. In his study, Moisture wicking in sportswear (1999), Havenith explains how sweating in sportswear helps cool the body by allowing loss of heat efficiently ANOVA for Quadratic model. The R^2 values of 0.9878 shown that the fabric wickability is predictable from independent variables of cutinase concentration, temperature and time.

The regression equation for wickability is given below:

$$\text{wickability} = 2.16 + 0.3875\text{A} + 0.2625\text{B} + 0.4\text{C} - 0.1500\text{AC} - 0.01\text{BC} - 0.1325A^2 + 0.2575C^2 \quad (7)$$

As cutinase concentration increases by one unit, wickability increases by 0.3875 units while other factors are constant. This implies that for larger amounts of enzymes there is a greater degradation of fabric structure which could enhance heat transfer capacities within materials through their increased ability to conduct heat. Raising wickability by 0.2625 constants for every degree rise in temperature while keeping other parameters same. Increased temperatures will probably lead to greater enzyme activity, which might alter the material structure allowing for ease of transmitting heat.

Well-tuned enzymatic actions of cutinase have been shown to considerably increase the cloth's water absorbency hence aiding in controlling moisture on a sportsman's apparel hence increasing comfort. With regard to cutinase concentration, the wickability of the fabric should decrease by 0.2375 units every time the temperature and time remain the same. Higher cutinase concentrations increase the capacity of the fabric to take in and expel water, as evident in the positive sign before the number. By catalyzing reactions that break down surface hydrophobic entities like greases or waxes that are left behind after production processes among others, cutinase enzymes promote hydrophilicity of fabrics. The enzyme treatments were shown to change the surface properties of polyester by increasing their hydrophilicities (Thomsen, Almdal and Meyer, 2023).

According to the regression analysis, an increase in temperature leads to improved wickability of the fabrics. The rise in the wickability of the fabrics by 0.2625 unit is related to a 1-degree increase in temperature while maintaining cutinase concentration and time. Higher temperatures can increase the activity of the cutinase enzyme and improves the fabric's affinity for water and the ability to drain it away. A study was done (Thomsen, Radmer and Meyer, 2024) which showed that rise in temperature substantially intensifies the performance of enzyme treatments on polyester fabrics. In addition, as the regression analysis shown that wickability of the fabric is positively influenced by treatment time. Longer treatment times increase cutinase enzyme activity thus improving hydrophilic properties of cloth materials. Nevertheless, requires optimizing treatment time so as not to possibly lead to too much treatment hence causing degradation to structure of the fabric. With optimum settings, enhancement is realized in general fabric wickability whereas moisture control is made possible through significant increment in efficiency of moisture management and overall comfort in sportswear applications.

5. CONCLUSION:

Cutinase enzymatic modifications of knitted fabrics have been shown to greatly improve their thermo-physiological comfort properties, thus rendering them suitable for use as sportswear. A slight morphological change was found in the SEM study, indicating minor surface erosion. Additionally, the FTIR spectroscopic analysis showed the creation of several new –OH and –COOH functional groups, enhancing the material's hydrophilic properties. And, the fabric's structural integrity was preserved despite the treatment's slight reduction in weight and tensile strength. The improved thermal comfort features of the enzymatically treated fabric are strongly correlated with its high R-square values (around 0.98) for both thermal properties and air permeability. And also, structurally modified knitted fabric can also significantly enhance the physical and thermal property of knitted fabrics. These results provide the textile industry important information in its drive for high-performance athletic wear by highlighting the possibility of employing enzymatic treatments to create better comfort and performance sports wears.

Acknowledgements
I would like to express my sincere gratitude to the Ethiopian Institute of Textile and Fashion Technology (EiTEX), Bahir Dar University, for providing the necessary materials and equipment to conduct this research. Their support was instrumental in the successful completion of this study.
Funding: No funding
Institutional Review Board Statement: If any
Data Availability Statement: if any
Declarations: There is no conflict of interests

REFERENCE:

Agarwal, R., Jassal, M. and Agrawal, A.K. (2021) ‘Nano surface modification of poly(ethylene terephthalate) fabrics for enhanced comfort properties for activewear’, *Journal of Industrial and Engineering Chemistry*, 98(April 2021), pp. 217–230. Available at: https://doi.org/10.1016/j.jiec.2021.03.050.

Ahmad, F. *et al.* (2023) ‘Recent Developments in Materials and Manufacturing Techniques Used for Sports Textiles’, *International Journal of Polymer Science*, 2023. Available at: https://doi.org/10.1155/2023/2021622.

Arnal, G. *et al.* (2023) ‘Assessment of Four Engineered PET Degrading Enzymes Considering Large-Scale Industrial Applications’, *ACS Catalysis*, 13(20), pp. 13156–13166. Available at: https://doi.org/10.1021/acscatal.3c02922.

Atalie, D., , Pavla Tesinova, Melkie Getnet Tadesse, , Eyasu Ferede, Ionut, D. and and Emil Loghin (2021) ‘Thermo-Physiological Comfort Properties of Sportswear with Different Combination of Inner and Outer Layers’, *Materials*, pp. 1–12.

Bielefeldt Bruun, M. and Langkjær, M.A. (2016) ‘Sportswear: Between Fashion, Innovation and Sustainability’, *Fashion Practice*, 8(2), pp. 181–188. Available at: https://doi.org/10.1080/17569370.2016.1221931.

Di Bisceglie, F. *et al.* (2022) ‘Cutinase-Catalyzed Polyester-Polyurethane Degradation: Elucidation of the Hydrolysis Mechanism’, *Polymers*, 14(3), pp. 1–12. Available at: https://doi.org/10.3390/polym14030411.

Chen, S. *et al.* (2013) ‘Cutinase: Characteristics, preparation, and application’, *Biotechnology Advances*, 31(8), pp. 1754–1767. Available at: https://doi.org/10.1016/j.biotechadv.2013.09.005.

Dave, H. *et al.* (2013) ‘Surface modification of polyester fabric by nonthermal plasma treatment and its effect on coloration using natural dye’, *Journal of Polymer Materials*, 30(3), pp. 291–304.

Ebrahimi, I. *et al.* (2011) ‘Atmospheric-air plasma enhances coating of different lubricating agents on polyester fiber’, *EPJ Applied Physics*, 56(1), pp. 1–10. Available at: https://doi.org/10.1051/epjap/2011100511.

El-Newashy, R.F. *et al.* (2019) ‘Evaluation of Comfort Attributes of Polyester Knitted Fabrics Treated with Sericin’, *Fibers and Polymers*, 20(9), pp. 1992–2001. Available at: https://doi.org/10.1007/s12221-019-9275-3.

Ferrario, V. *et al.* (2016) ‘Nature inspired solutions for polymers: Will cutinase enzymes make polyesters and polyamides greener?’, *Catalysts*, 6(12). Available at: https://doi.org/10.3390/catal6120205.

Getnet, M. and Chavan, R. (2015) ‘Catalyzation of alkaline hydrolysis of polyester by oxidizing agents for surface modification’, *International Journal of Sciences: Basic and Applied Research*, 22(2), pp. 232–252. Available at: https://pdfs.semanticscholar.org/b7d7/92071b45c4663ea4c589b4378bbee458abd9.pdf.

Gigli, M. *et al.* (2019) ‘Enzymatic hydrolysis of poly(1,4-butylene 2,5-thiophenedicarboxylate) (PBTF) and poly(1,4-butylene 2,5-furandicarboxylate) (PBF) films: A comparison of mechanisms’, *Environment International*, 130(April), p. 104852. Available at:

https://doi.org/10.1016/j.envint.2019.05.046.

Govindachetty, G., Sidhan, P. and Venkatraman, K.C. (2014) 'Thermo-physiological comfort properties of polyester and polyester/acrylic blended synthetic fabrics treated with herbal finishes', *Journal of Engineered Fibers and Fabrics*, 9(3), pp. 115–119. Available at: https://doi.org/10.1177/155892501400900313.

Gross, R.A., Ganesh, M. and Lu, W. (2010) 'Enzyme-catalysis breathes new life into polyester condensation polymerizations', *Trends in Biotechnology*, 28(8), pp. 435–443. Available at: https://doi.org/10.1016/j.tibtech.2010.05.004.

Gupta, D., Chaudhary, H. and Gupta, C. (2015) 'Topographical changes in polyester after chemical, physical and enzymatic hydrolysis', *Journal of the Textile Institute*, 106(7), pp. 690–698. Available at: https://doi.org/10.1080/00405000.2014.934046.

Kanelli, M. *et al.* (2015) 'Surface modification of poly(ethylene terephthalate) (PET) fibers by a cutinase from Fusarium oxysporum', *Process Biochemistry*, 50(11), pp. 1885–1892. Available at: https://doi.org/10.1016/j.procbio.2015.08.013.

Khalil, A., Těšinová, P. and Aboalasaad, A.R.R. (2022) 'Effect of Lycra Weight Percent and Loop Length on Thermo-physiological Properties of Elastic Single Jersey Knitted Fabric', *Autex Research Journal*, 22(4), pp. 419–426. Available at: https://doi.org/10.2478/aut-2021-0030.

Kumar, J.A. and Senthil Kumar, M. (2020) 'A Study on Improving Dyeability of Polyester Fabric Using Lipase Enzyme', *Autex Research Journal*, 20(3), pp. 243–249. Available at: https://doi.org/10.2478/aut-2019-0030.

Lee, S.H. and Song, W.S. (2010) 'Surface modification of polyester fabrics by enzyme treatment', *Fibers and Polymers*, 11(1), pp. 54–59. Available at: https://doi.org/10.1007/s12221-010-0054-4.

Liang, X. and Zou, H. (2022) 'Biotechnological Application of Cutinase: A Powerful Tool in Synthetic Biology', *SynBio MDPI*, 1(1), pp. 54–64. Available at: https://doi.org/10.3390/synbio1010004.

Martínez, A. and Maicas, S. (2021) 'Cutinases: Characteristics and insights in industrial production', *Catalysts MDPI*, 11(10). Available at: https://doi.org/10.3390/catal11101194.

Matsumura, S. *et al.* (2008) 'Enzymatic and Chemical Hydrolysis of Poly(ethylene terephthalate) Fabrics', *Journal of Polymer Science: Part A: Polymer Chemistry*, 46(April), pp. 7207–7224. Available at: https://doi.org/10.1002/pola.

Maurya, A., Bhattacharya, A. and Khare, S.K. (2020) 'Enzymatic Remediation of Polyethylene Terephthalate (PET)–Based Polymers for Effective Management of Plastic Wastes: An Overview', *Frontiers in Bioengineering and Biotechnology*, 8(November), pp. 1–13. Available at: https://doi.org/10.3389/fbioe.2020.602325.

Mounir, H. *et al.* (2012) 'Influence of Sportswear Fabric Properties on the Health and Performance of Athletes', *Fibres and Textiles in Eastern Europe*, 20(4), pp. 82–88.

Nasrin, S. *et al.* (2023) 'Factors Affecting the Sweat-Drying Performance of Active Sportswear—A Review', *Textiles MDPI*, 3(3), pp. 319–338. Available at: https://doi.org/10.3390/textiles3030022.

Nemani, S.K. *et al.* (2018) 'Surface Modification of Polymers: Methods and Applications', *Advanced Materials Interfaces*, 5(24), pp. 1–26. Available at: https://doi.org/10.1002/admi.201801247.

Oeser, T. *et al.* (2010) 'High level expression of a hydrophobic poly (ethylene terephthalate) - hydrolyzing carboxylesterase from Thermobifida fusca KW3 in Escherichia coli BL21 (DE3)', *Journal of Biotechnology*, 146, pp. 100–104. Available at: https://doi.org/10.1016/j.jbiotec.2010.02.006.

Özdil, N., Marmarali, A. and Kretzschmar, S.D. (2007) 'Effect of yarn properties on thermal comfort of knitted fabrics', *International Journal of Thermal Sciences*, 46(12), pp. 1318–1322. Available at: https://doi.org/10.1016/J.IJTHERMALSCI.2006.12.002.

Park, M. *et al.* (2014) 'Combined effect of corona discharge and enzymatic treatment on the mechanical and surface properties of wool', *Journal of Industrial and Engineering Chemistry*, 20(1), pp. 179–183. Available at: https://doi.org/10.1016/j.jiec.2013.04.010.

Parvinzadeh, M. (2012) 'Surface modification of synthetic fibers to improve performance: recent approaches.', *Global Journal of Physical Chemistry*, 3(December), pp. 2/1-2/11. Available at: http://www.simplex-academic-publishers.com/gjpc.aspx?b=2.

Quartinello, F. *et al.* (2017) 'Synergistic chemo-enzymatic hydrolysis of poly(ethylene terephthalate) from textile waste', *Microbial Biotechnology*, 10(6), pp. 1376–1383. Available at: https://doi.org/10.1111/1751-7915.12734.

Ribitsch, D. *et al.* (2012) 'A New Esterase from Thermobifida halotolerans Hydrolyses Polyethylene Terephthalate (PET) and Polylactic Acid (PLA)', *Polymer*, pp. 617–629. Available at: https://doi.org/10.3390/polym4010617.

Ribitsch, D. *et al.* (2015) 'Enhanced Cutinase-Catalyzed Hydrolysis of Polyethylene Terephthalate by Covalent Fusion to Hydrophobins', *Applied and Environmental Microbiology* [Preprint], (12). Available at: https://doi.org/10.1128/AEM.04111-14.

Roy Choudhury, A.K., Majumdar, P.K. and Datta, C. (2011) *Factors affecting comfort: human physiology and the role of clothing*, *Improving Comfort in Clothing*. Available at: https://doi.org/10.1533/9780857090645.1.3.

Silva, C.M. *et al.* (2005) 'Cutinase — A New Tool for Biomodification of Synthetic Fibers', *Journal of polymer science*, 43, pp. 2448–2450. Available at: https://doi.org/10.1002/pola.20684.

Tegegne, W. and Haile, A. (2024) 'Effect of papain enzyme surface modification on hydrophilic and comfort properties of polyester / cotton blend fabric', *Discover Materials* [Preprint]. Available at: https://doi.org/10.1007/s43939-023-00071-5.

Thomsen, T.B., Almdal, K. and Meyer, A.S. (2023) 'Significance of poly(ethylene terephthalate) (PET) substrate crystallinity on enzymatic degradation', *New Biotechnology*, 78(November 2023), pp. 162–172. Available at: https://doi.org/10.1016/j.nbt.2023.11.001.

Thomsen, T.B., Radmer, T.S. and Meyer, A.S. (2024) 'Enzymatic degradation of poly(ethylene terephthalate) (PET): Identifying the cause of the hypersensitive enzyme kinetic response to increased PET crystallinity', *Enzyme and Microbial Technology*, 173(November 2023), pp. 1–7. Available at: https://doi.org/10.1016/j.enzmictec.2023.110353.

Toprak, T. and Anis, P. (2020) 'The effect of enzymatic modification on the dyeability of polyester fabric with reactive dye', *AATCC Journal of Research*, 7(6), pp. 41–47. Available at: https://doi.org/10.14504/ajr.7.6.6.

Vertommen, M.A.M.E. *et al.* (2005) 'Enzymatic surface modification of poly(ethylene terephthalate)', *Journal of Biotechnology*, 120(4), pp. 376–386. Available at: https://doi.org/10.1016/j.jbiotec.2005.06.015.

Weinberger, S. *et al.* (2017) 'Enzymatic degradation of poly(Ethylene 2,5-furanoate) powders and amorphous films', *Catalysts*, 7(11). Available at: https://doi.org/10.3390/catal7110318.

Yang, Z. *et al.* (2010) 'Crystallization behavior of poly(ε-caprolactone)/layered double hydroxide nanocomposites', *Journal of Applied Polymer Science*, 116(5), pp. 2658–2667. Available at: https://doi.org/10.1002/app.

Yetisen, A.K. *et al.* (2016) 'Nanotechnology in Textiles', *ACS Nano*, 10(3), pp. 3042–3068. Available at: https://doi.org/10.1021/acsnano.5b08176.