

Influence of Yarn Linear Density and Weave Interlacement on the Dynamic Response of Woven Temperature Sensors

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Abstract

The structural configuration of textile sensors plays a decisive role in determining their thermal response characteristics and long-term stability. This study systematically investigates the influence of weave architecture, yarn linear density, and ply number on the performance of woven temperature sensors fabricated using silver-coated polyamide conductive yarns. Eight sensor configurations were developed by combining two weave types (plain and twill), two yarn counts (117/17 and 235/36 dtex), and two-ply arrangements (single and two-ply). The conductive yarn was inserted in the weft direction within a polyester base structure to ensure controlled positioning and electrical isolation.

Thermal characterization was conducted in a laboratory-controlled environment over a temperature range of 30–60 °C with 5 °C increments. Electrical resistance was measured at each stabilized temperature, and temperature coefficients of resistance (TCR), linearity, thermal time constants, and cyclic stability were evaluated. All sensor configurations exhibited a stable and linear positive temperature coefficient behavior, with TCR values ranging from 2.51×10^{-3} to $2.91 \times 10^{-3} \text{ }^{\circ}\text{C}^{-1}$ and regression coefficients exceeding 0.99. Statistical analysis confirmed temperature as the dominant factor affecting resistance, while structural parameters primarily influenced the magnitude and dynamic response of the signal.

Twill weave structures consistently demonstrated faster thermal response, with heating time constants between 4.8–5.6 s compared to 6.1–7.2 s for plain weaves. This behavior is attributed to reduced interlacement density and lower effective thermal mass in twill fabrics, which facilitate improved heat transfer. In contrast, plain weave sensors exhibited slightly enhanced resistance stability during cyclic testing, with resistance drift remaining below 1.5% for all configurations after repeated heating–cooling cycles.

The results reveal a measurable trade-off between response speed and structural stability, highlighting weave architecture as a critical design parameter in textile-based temperature sensors. These findings provide practical guidance for optimizing woven sensor structures for wearable monitoring and smart textile applications without modifying the sensing material itself.

Index Terms—Conductive yarns, plain weave, ply effect, smart textiles, temperature sensors, twill weave, woven composites

I. INTRODUCTION

Smart textiles are defined as type of textile materials that can sense [1] and respond [2] to environmental change in restricted way [3]. Over the time, they are also referred as electronic textiles (e-textiles), intelligent textiles, and functional fabrics. Recent bibliometric analysis by [4] included a total number of 5810 documents till 2022. This highlights the importance of this emerging field in vast applications of wearable smart textiles, non-wearable structural applications as well as environmental monitoring. These developments highlight the importance of integrating sensing capabilities directly into textile structures.

These smart textiles are integrated to be used in different applications including strain sensing, pressure, temperature and shape memory systems. Heitor Luiz et al. [5] discussed recent developments and associated challenges in their fabrication as well as application areas. Among all these application areas, temperature sensing is particularly significant as it is one of the direct physiological functions of human skin [6]. Environmental change can be continuously monitored and detected by human skin as it responds to thermal stimuli. This can help us to continuously record and maintain thermoregulation. As a result, monitoring temperature plays an important role in identifying physiological abnormalities, preventing injuries, and providing information about the surrounding environment [7].

Body temperature has long been considered a key clinical indicator, as deviations from the normal range may signal underlying health conditions. Under normal conditions, the human body maintains a

stable temperature typically between 36.5 °C and 37.5 °C [8,9]. Therefore, temperature sensors intended for skin monitoring must be capable of detecting small and continuous temperature variations with high accuracy and stability. In particular, reliable sensors should be sensitive enough to measure temperature changes of approximately $\pm 0.1 \text{ }^{\circ}\text{C}$ within the clinically relevant range of 37 °C to 39 °C, and about $\pm 0.2 \text{ }^{\circ}\text{C}$ outside this range, to ensure accurate physiological monitoring and early detection of abnormalities [10].

Flexible temperature sensors generally consist of three main functional components: a flexible substrate, an active sensing material, and conductive electrodes. These sensors operate based on changes in electrical resistance in response to temperature variations, which allows real-time temperature monitoring [11,12] reviewed flexible temperature sensors based on nanomaterials and conductive polymers, highlighting their advantages in sensitivity and flexibility, while also identifying key limitations related to temperature accuracy, mechanical stability, long-term durability, and stretchability.

Non-woven fabrication techniques are also explored for development of Textile based temperature sensors. For example, a melt-blown nonwoven temperature sensor demonstrated high sensitivity of $-0.737 \text{ }^{\circ}\text{C}^{-1}$, excellent linearity ($R^2 = 0.98$), and a temperature resolution of $0.1 \text{ }^{\circ}\text{C}$ within the range of 25 °C to 45 °C. The sensor also exhibited good cyclic stability and long-term performance. However, despite these promising sensing characteristics, the fabrication process was relatively complex, which may limit its scalability and large-scale industrial implementation [13].

A. Textile Fabrication Methods for Temperature Sensors

Textile temperature sensors can be fabricated using knitting, printing, and weaving techniques, each offering distinct advantages and limitations.

Printed textile sensors use conductive inks such as graphene, carbon nanotubes, or silver nanoparticles deposited onto textile substrates. [14]. Modified printers use conductive filaments to print directly onto textile substrates [15]. Researcher used PP NW and carbon ink achieving Temperature sensitivity of $0.447\% \text{ } ^\circ\text{C}^{-1}$. Further research on Resistive sensors with cotton printed with conductive polymers, CNTS and graphene resulted in Low durability and high drift as conductive layers may crack, delaminate, or degrade under mechanical stress, washing, or repeated use and it has to be integrated [16]. Integrating sensors directly into textiles during the weaving or knitting process proposes seamless incorporation and durability

Knitted sensors provide excellent flexibility and stretchability due to their looped structure [17], allowing good conformity to curved surfaces. Atalay et al used different conductive yarns and base yarn to study sensing properties between the temperature range of $20\text{--}60\text{ }^\circ\text{C}$ [18] demonstrating achievable wearable temperature sensing range. Other studies showed that knitted structure provide good sensitivity and thermal responsiveness [19]. But with mechanical deformation, the looped structure creates structural instability, which leads to signal fluctuation, hysteresis, and decreased repeatability [20].

Mechanical stability is better provided by woven structures as they offer interlaced warp and weft yarns at right angle which is also beneficial in terms of consistent electrical paths. Woven sensors have a promising. Through various weave designs, conductive parts may be precisely positioned and sensing qualities can be tailored as per requirement by different interlacing patterns of warp and weft yarns [21]. Mattana inserted conductive yarn only in weft direction to avoid possible wear and tear in warp direction after every three non-conductive weft yarns. Twill weave structure was explored owing to little flexible yet providing mechanical stability, these woven temperature sensors showed linear trend with temperature with good repeatability [22]. Similarly, woven designs with Conductive yarns interwoven in both the warp and weft coefficient of resistance values reaching $0.00213\text{ }^\circ\text{C}^{-1}$, linearity orientations showed dependable and useful temperature sensing capability [23]. However, the conductive yarn in single woven sensor remains exposed to environmental condition which can oxidized over time. Mechanical stresses can also reduce durability over time so to address this, multilayer woven sensors are also explored. In the $20\text{--}50\text{ }^\circ\text{C}$ range, a double-layer woven temperature sensor demonstrated exceptional performance, including a high temperature coefficient of resistance ($>0.00213\text{ }^\circ\text{C}^{-1}$), robust linearity ($>98\%$), and low hysteresis ($\sim 3.65\%$) [24]. Another study on double-layer tubular woven fabrics found that the layered structure boosted thermal resistance, but the larger thermal mass caused a minor delay in response time concluding that structural yarn properties are just as important as weave architecture [25] demonstrated the role of weave pattern, density, and yarn orientation on sensitivity for wearable sensing applications.

B. Effect of Yarn Linear Density, Ply, and Weave Structure

Yarn linear density, number of ply in yarn and their weaving pattern combinedly form the structural properties of woven fabric. These structural parameters are key parameters for determining thermal response, sensitivity and electrical stability. Researchers observed a considerable decrease in resistivity as yarn thickness and ply number increased after conducting a comprehensive evaluation of the effects of yarn linear density and ply in woven temperature sensors. In

particular, the resistivity of conductive yarn with a linear density of 60.4 tex was about $55\text{ }\Omega/\text{m}$, while that of finer yarns was about $250\text{ }\Omega/\text{m}$. By regulating conductive yarn location, contact stability, and heat transfer behaviour, weave architecture has a significant impact on temperature sensing performance in addition to yarn thickness and ply. The amount of contact sites, yarn exposure, and structural integrity of the conductive network are all determined by the interlacement design. Twill and multilayer weaves offer longer floats and greater structural flexibility, impacting both electrical continuity and thermal conduction paths, whilst plain weaves offer maximal interlacement and structural stability [18].

Ivo Locher presented a hybrid woven construction that used controlled tension to interlace polyester strands with copper wire. The polyester yarns added mechanical strength and dimensional stability, while the copper offered reliable electrical conductivity and effective heat transmission. Reliable electrical performance and quick thermal responsiveness were made possible by this combination. In a similar vein, layered woven structures have been created to shield electrical components from environmental exposure and mechanical harm [9]. For instance, a dual-layer woven structure with platinum conducting parts sandwiched between two protective layers reduced mechanical wear and oxidation, maintained steady electrical spacing, and greatly increased longevity.

Weaving techniques have also been successfully used to fabricate textile thermocouples in addition to resistance-based sensors. over 98%, and low hysteresis of roughly 3.65% within the $20\text{--}50\text{ }^\circ\text{C}$ temperature range, multilayer woven temperature sensors have proven to offer exceptional sensing capability.

Cheung used industrial weaving techniques to create flexible thermocouples that were included into cotton garments that were simply woven. With radii ranging from 0.5 to 5 cm, these woven thermocouples showed outstanding electrical stability and mechanical resilience, with resistance variation staying below 0.01 under repeated bending circumstances. This demonstrates that dependable and scalable temperature sensing structures are made possible by carefully regulating the thread arrangement during weaving [26].

Despite many studies on individual yarn and weave parameters, little research has looked closely at how yarn linear density, ply, and weave design work together to affect woven textile temperature sensors. This study aims to address this gap by evaluating how these structural factors impact sensitivity, linearity, response time, and mechanical stability. The goal is to enhance textile-based temperature sensors for both wearable and industrial uses.

II. MATERIALS AND METHODS

This section highlights the variable parameters used in this research, type of weave (Twill and Plain), Yarn count (117/17 and 235/36) and no of ply (1 and 2 ply) to investigate their effect on Temperature coefficient of Resistance, Response time, hysteresis and Temperature cyclic Testing. Eight different flexible woven temperature-sensors were fabricated in which base yarn is polyester used in warp direction and in weft in between conductive yarns to avoid contacting each other. The conductive yarn is used only in weft direction with polyester yarns in between. Samples were then connected to digital auto range Fluke multimeter while the samples are placed in curing oven. Schematic view of whole methodology is given in Fig. 1.

TABLE I

Comparative summary of textile temperature sensors fabricated using different manufacturing methods. Data compiled from using different manufacturing methods. Data compiled from literature shows the range of conductive materials, operating temperatures, sensitivity (TCR or $\% ^\circ\text{C}^{-1}$), linearity (R^2), response time

Fabrication Method	Conductive Material	Temperature Range ($^\circ\text{C}$)	Sensitivity / TCR	Linearity (R^2)	Response Time	Durability / Stability	Reference
Melt-blown Nonwoven	Conductive polymer composite	25-45	- 0.737 $\% ^\circ\text{C}^{-1}$	0.98	Not reported	Good cyclic stability	[23]
Knitting	Silver -coated PA yarn	20-60	0.0038 $\% ^\circ\text{C}^{-1}$ (approx.)	>0.95	8-12 s (estimated)	Moderate; signal variation under strain	[17]
Printing on Textiles	Carbon black/PP nonwoven	25-45	0.447 $\% ^\circ\text{C}^{-1}$	>0.96	Not reported	Low; cracking/delamination	[19]
Printing on Textiles	CNT/graphene/Ag nanoparticles	20-60	0.52 $\% ^\circ\text{C}^{-1}$	0.95	Not reported	Low -moderate	[11]
Woven (Plain)	Silver -coated PA (60.4 tex)	20-70	0.0025 - 0.0039 $\% ^\circ\text{C}^{-1}$	>0.97	6-10 s	Good	[18]
Woven (Twill 1/8)	Conductive yarn (weft inserts)	25-50	0.0032 $\% ^\circ\text{C}^{-1}$	>0.98	5-8 s	Good	[14]
Woven (Bidirectional)	Conductive yarns (warp + weft)	20-60	0.0028 $\% ^\circ\text{C}^{-1}$	>0.96	7-10 s	Good	[5]
Woven (Double - layer)	Conductive yarns	20-50	>0.00213 $\% ^\circ\text{C}^{-1}$	>98%	Slightly delayed	Excellent	[22]

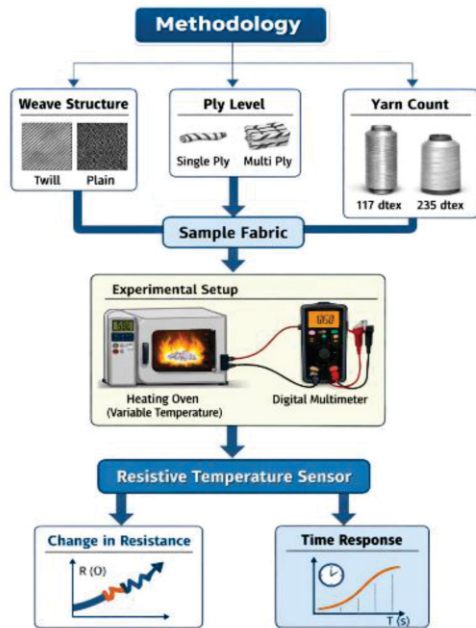


Fig. 1. Schematic diagram of the research methodology showing the experimental workflow. The study investigates three variable parameters: weave structure (plain vs. twill), yarn linear density (117/17 vs. 235/36 dtex), and ply number (single vs. two-ply)

A. Conductive yarn

Two different electrically conductive yarns were used in this research i) Shieldex 117/17 + B (a) and ii) Shieldex 235/36 (b). These conductive yarns being silver-coated, providing thermal and electrical conductivity were acquired from Shieldex Trading Inc. (Bremen, Germany). Both yarns were made from high-strength Polyamide/Nylon 6.6 and coated with 99.9% pure silver. After being coated with silver, Shieldex 117/17 + B had a yarn count of 140 dtex, a raw yarn count of 117 dtex, and a resistivity of around $1.5 \text{ K}\Omega/\text{m}$. On the other hand, Shieldex 235/36 had a yarn count of 290 dtex after silver coating, a raw yarn count of 235 dtex, and a resistivity of approximately $2.5 \text{ K}\Omega/\text{m}$. The following table (Table II) lists these electrically conductive yarns' key characteristics.



Fig. 2. Silver-coated polyamide conductive yarns used as sensing elements: (a) Shieldex® 235/36 (single-ply) and (b) Shieldex® 117/17 (single-ply)

B. Fabrication of Temperature sensing fabric

A manual dobby shuttle loom was used for manufacturing woven temperature sensor as shown in Fig. 3. Manual operation allows careful and customized placement of conductive yarn in weft direction while minimizing the risk of wear and tear. Manufacturing process followed drafting plan and pattern sequence for both plain and twill weave. Polyester yarn was first beamed ensuring consistent ends per inch while passing through reed. One conductive yarn was inserted after every three picks of polyester yarns in weft direction to keep consistent picks per inch. Polyester yarn will act as structural yarn while being an electrical insulator, meaning it does not conduct electricity, which makes it ideal as a base yarn in applications where electrical isolation is required alongside textile functionality. Shieldex nylon coated yarn will act as functional yarn that will pass through it. Eight different samples by varying weave structure, no of ply and conductive yarn were manufactured with three replicates each according to the table given below.

C. Measuring the Temperature Coefficient of Resistance

A laboratory-scale curing oven, also known as the heating chamber, was utilised to create a regulated and consistent thermal environment for the temperature sensing tests. With an accuracy of about $\pm 1^\circ\text{C}$, the curing oven provides dependable temperature stability, guaranteeing accurate and consistent temperature exposure of the woven sensor samples. The curing oven offers a stable and dependable platform for assessing the temperature-dependent electrical behaviour of conductive textile sensors, despite the fact that its heat transfer properties differ from those of real-world applications. The temperature sensor was hung inside the curing oven and a thermometer is attached with it to measure temperature of fabric rather than relying on oven digital display. Two conductive ends of woven temperature sensor were connected to Fluke digital auto range multimeter, which ensures high accuracy and automatically selects the appropriate measurement range to minimize error. Multimeter was placed outside the curing oven and initial resistance was recorded.

The temperature inside the curing oven was increased at increments of 5°C after every 3 minutes so that it can achieve 63.2 % change in resistance. Temperature range was set from 30°C to 60°C . To ensure

TABLE II

Physical and electrical properties of Shieldex® silver-coated polyamide 6.6 conductive yarns used in this study.

Property / Yarn Type	Shieldex 117/17 + B	Shieldex 117/17 + B ×2	Shieldex 235/36	Shieldex 235/36 ×2
Metal Plated	99.9 % Pure Silver (+B coating)	99.9 % Pure Silver	99.9 % Pure Silver	99.9 % Pure Silver (+B)
Yarn Count (raw)	117 dtex	117 dtex (×2 ply twisted)	235/36 dtex	Raw 476 dtex (×2 ply)
Yarn Count (silverized)	140 ± 6 dtex	280 dtex (×2 ply)	295 dtex	590 ± 15 dtex
Electrical Resistivity		< 1.5 kΩ/m		< 80 Ω/m ± 30 Ω/m

TABLE III

Experimental design matrix showing the eight woven sensor configurations. Each configuration combines a specific conductive yarn with no of ply and weave structure.

S.R No	Base Yarn	Cond Yarn	Weave type	Replicates
1	Polyester	Shieldex 235/36	Plain Weave	3
2	Polyester	Shieldex 235/36x2		3
3	Polyester	Shieldex 117/17		3
4	Polyester	Shieldex 117/17 x 2		3
5	Polyester	Shieldex 235/36	Twill Weave	3
6	Polyester	Shieldex 235/36x2		3
7	Polyester	Shieldex 117/17		3
8	Polyester	Shieldex 117/17 x 2		3

that the fabric sensor reached thermal equilibrium and that the measured resistance represented the steady-state situation rather than transient thermal influences, a stabilization period of 2.5 minutes was permitted at each temperature. After stabilization, 10 resistance readings were recorded by using Fluke digital multimeter at fixed intervals. Those ten readings were then average to get reliable resistance value. This systematic approach helps us to identify and eliminate outliers if any ensuring reliable characterization of the temperature sensor. All measurements were conducted under identical conditions to ensure repeatability, consistency, and experimental reliability.

D. Response Time Evaluation

For effective temperature monitoring, textile-based sensors must respond quickly to changes in environmental conditions. In many conventional designs, the conductive yarn is embedded within or completely surrounded by insulating fibers, which increases thermal resistance and delays heat transfer to the sensing element. In the present work, however, the silver-coated conductive yarn was introduced directly as a weft component within the woven polyester structure and remained exposed to the heated air inside the curing oven. This configuration reduced thermal insulation around the sensing yarn and enabled more efficient convective heat transfer, leading to a faster thermal response and improved sensing performance.

To examine the response behavior, the woven sensor samples were first allowed to stabilize at room temperature ($25 \pm 1^\circ\text{C}$) for 3 minutes to establish a consistent baseline resistance. The samples were then transferred to a laboratory-scale curing oven, where the temperature was gradually increased from 30°C to 60°C in 5°C increments at 3-minute intervals. Because the conductive yarn was directly exposed



Fig. 3. Manufacturing of woven temperature sensors using a manual dobby handloom. pattern

to the heated air, heat transfer to the sensing element occurred quickly. At each temperature step, the samples were held for 2.5 minutes to ensure thermal equilibrium between the conductive yarn and the surrounding environment before recording the resistance values.

The electrical resistance of the conductive yarn was measured using a Fluke digital auto-range multimeter to ensure accurate and stable resistance measurements. At each temperature level, ten readings were recorded after thermal stabilization, and the average value was calculated to minimize random fluctuations and enhance data reliability.

Integrating the conductive yarn directly as an exposed sensing element within the woven polyester structure facilitated more efficient heat transfer compared to configurations where the sensor is fully embedded or insulated. As a result, the resistance responded rapidly to temperature variations, demonstrating the suitability of the woven architecture for reliable and accurate temperature sensing.

E. Temperature Cyclic Test

To assess repeatability and thermal stability, a cyclic temperature test was performed under repeated heating and cooling conditions. The fabric samples were placed inside a laboratory-scale curing oven, and the temperature was cycled between 30 °C and 60 °C. Each temperature level was maintained for 3 minutes, followed by a 2.5-minute stabilization period to allow thermal equilibrium before measurements were taken.

Resistance measurements were again obtained using the Fluke digital auto-range multimeter. Ten readings were recorded and averaged at each temperature step to improve accuracy. The heating and cooling sequence was repeated for several cycles under identical conditions. The consistency of resistance values across these cycles was used to evaluate the sensor's repeatability and overall thermal stability.

F. Hysteresis Analysis

Hysteresis analysis was performed to evaluate the difference in resistance during heating (30–60 °C) and cooling (60–30 °C) cycles at the same temperature points. Resistance measurements were recorded after a stabilization period of 2.5 minutes at each temperature, and the average of 10 readings was calculated.

$$\Delta H = \frac{(\Delta R_H)_{\max}}{R_{FS}} \times 100\% \quad (1)$$

where $(\Delta R_H)_{\max}$ is the maximum resistance difference at the same temperature during heating and cooling, and $R_{FS} = R_{\max} - R_{\min}$ is the full-scale resistance range.

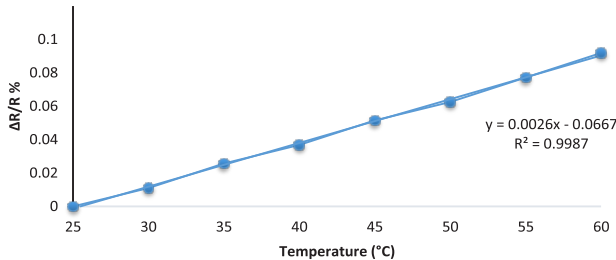


Fig. 4. Relative resistance change ($\Delta R/R_0 \times 100\%$) as a function of temperature for Sample 1 (plain weave, 235/36 dtex single-ply).

Measurements were taken from 30°C to 60°C in 5°C increments with 2.5-minute stabilization at each step. Data points represent the mean of 10 measurements; error bars indicate standard deviation. Linear regression (solid line) yields $R^2 = 0.9987$, confirming excellent linearity of the temperature-resistance relationship.

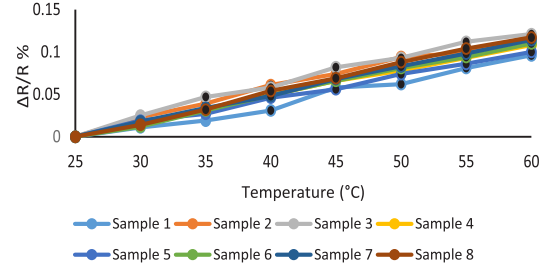


Fig. 5. Relative resistance change ($\Delta R/R_0 \times 100\%$) as a function of temperature for all eight woven sensor configurations (S1-S8). Each data point represents the mean of three replicate samples with 10 measurements each. All configurations show linear positive temperature coefficient behavior, with slopes corresponding to TCR values ranging from 2.51×10^{-3} to $2.91 \times 10^{-3} \text{ } ^\circ\text{C}^{-1}$.

where $(\Delta R_H)_{\max}$ is the maximum resistance difference at the same temperature during heating and cooling, and $R_{FS} = R_{\max} - R_{\min}$ is the full-scale resistance range.

A low hysteresis value indicates good repeatability, stability, and reliable temperature sensing performance of the woven conductive yarn sensor.

III. RESULT

A. Temperature Coefficient of Resistance of the Temperature Sensing Yarns

In RTDs, the temperature coefficient of resistance is measured to predict the sensitivity of the sensor. The resistance of metals vary linearly with temperature. This can be obtained using the following equation:

$$R_t = R_{ref}(1 + \alpha(T - T_{ref})) \quad (2)$$

where R_t is the resistance at temperature T in degrees Celsius, R_{ref} is the reference resistance at 30 °C, α is the temperature coefficient of resistance, and T_{ref} is the reference temperature (30 °C) at which α is specified

The woven textile sensors showed clear and repeatable response to temperature from 25 °C to 60 °C. All eight configurations combining plain and twill weaves, 117/17 and 235/36 yarn counts, and single vs two-ply exhibited linear increase in resistance with rising temperature. This confirms the positive temperature coefficient behavior of Shieldex silver-coated conductive yarns.

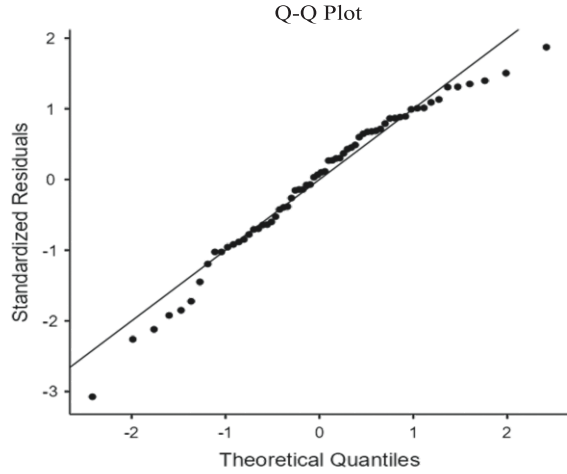
Temperature coefficient of resistance (α) values ranged from 2.51×10^{-3} to $2.91 \times 10^{-3} \text{ } ^\circ\text{C}^{-1}$, indicating excellent sensitivity comparable to or better than existing textile-based temperature sensors.

TABLE IV
ANCOVA - Sensitivity

	Sum of Squares	Df	Mean Squares	F	P	η^2p
Overall model	0.0818	15	0.00545	591.58	<.001	
Sample	8.66e-5	7	1.24e-5	1.30	0.272	0.159

TABLE V
ANCOVA - Sensitivity

	Sum of Squares	Df	Mean Squares	F	P	η^2p
Temp	0.0813	1	0.08127	8519.10	<.001	0.994
Sample*Temp	4.66e-4	7	6.66e-5	6.98	<.001	0.504
Residuals	4.58e-4	48	9.54e-6			
Homogeneity of Variances Test (Levene's)						Normality Test (Shapiro-Wilk)
	F	df1	df2	P	Statistic	P
	1.79	7	56	0.108	0.970	0.114



The ANCOVA analysis confirms that temperature is the main factor influencing the resistance of the woven textile sensors, with a highly significant effect observed across all configurations ($p < 0.001$), which supports the strong linear resistance–temperature relationship shown in the experimental results. The interaction between temperature and sensor configuration was also statistically significant, indicating that structural parameters such as weave type, yarn linear density, and ply number slightly affect the sensitivity, even though all samples maintained consistent linear behavior. In contrast, the baseline differences between samples alone were not statistically significant, suggesting that structural variations do not alter the sensing mechanism itself but mainly influence the degree of response. The statistical assumptions were satisfied, confirming the reliability of the analysis. Overall, these findings demonstrate that temperature governs the resistance behavior, while textile structural design plays an important role in optimizing sensitivity without affecting the fundamental sensing performance.

B. Temperature Cycling and Repeatability

All eight configurations were subjected to **five heating-cooling cycles** from $30 \pm 0.5^\circ\text{C}$ to $60 \pm 0.5^\circ\text{C}$. Resistance at $25 \pm 0.5^\circ\text{C}$ was recorded after each cycle to assess hysteresis and repeatability.

IV. DISCUSSION

The experimental results clearly show that the thermal behavior of the woven sensors is not governed solely by the conductive yarn itself, but strongly influenced by the fabric architecture. Across all yarn counts and ply configurations, twill fabrics consistently responded more quickly during both heating and cooling. This difference is most

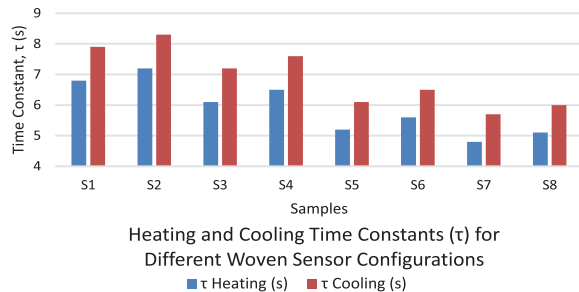


Fig. 5. Thermal time constants for heating (τ_h) and cooling (τ_c) of all eight sensor configurations. Bars represent mean values from three replicate samples; error bars indicate standard deviation. Twill weave configurations (S5-S8) consistently show faster response (4.8-5.6 s heating, 5.7-6.5 s cooling) compared to plain weave (6.1-7.2 s heating, 7.2-8.3 s cooling). Finer yarns (117/17 dtex) exhibit marginally faster response than coarser yarns (235/36 dtex), while ply number shows minimal effect.

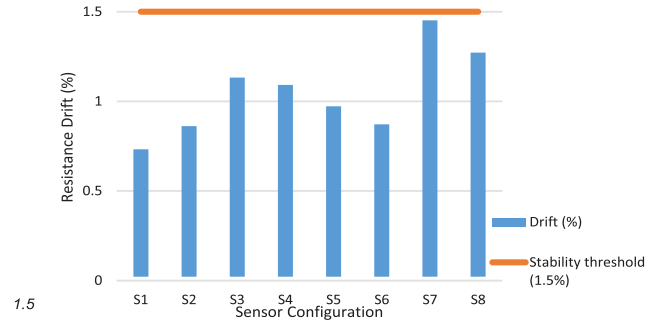


Fig. 6. Resistance drift after five thermal cycles between 30°C and 60°C . Bars show percentage change in resistance at 25°C from initial to final cycle; error bars represent propagated standard deviation. All configurations exhibit drift below 1.5%, demonstrating excellent stability. Plain weave sensors (S1-S4) show lower drift (0.71-1.11%) than twill weave sensors (0.95-1.43%). Two-ply configurations (even-numbered samples) show marginally lower drift than their single-ply counterparts.

plausibly linked to structural characteristics of the weave. Twill constructions contain longer floats and fewer interlacement points than plain weaves, which reduces structural compactness and likely lowers the effective thermal mass of the sensing zone. In addition, reduced yarn crimp in twill fabrics may facilitate more direct exposure of the conductive filament to the surrounding air, enhancing convective heat transfer and shortening the time required to reach thermal equilibrium.

TABLE VI
ANCOVA - Heating (s)

	Sum of Squares	Df	Mean Square	F	P	η^2p
Overall model	15.986	7	2.2837	6.817	<.001	
Weave	13.054	1	13.0537	38.966	<.001	0.709
Yarn	2.831	3	0.9437	2.817	0.072	0.346
Weave * Yarn	0.101	3	0.0337	0.101	0.958	0.019
Residuals	5.360	16	0.3350			

TABLE VII
ANCOVA - Cooling (s)

	Sum of Squares	Df	Mean Square	F	P	η^2p
Overall model	19.766	7	2.8237	5.1224	0.003	
Weave	16.834	1	16.8337	30.5374	<.001	0.656
Yarn	2.831	3	0.9438	1.7120	0.205	0.243
Weave * Yarn	0.101	3	0.0338	0.0612	0.979	0.011
Residuals	8.820	16	0.5512			

When yarn linear density was considered, the finer 117/17 yarn exhibited slightly faster response compared to the coarser 235/36 yarn under identical weave conditions. Although the difference was modest, it can reasonably be associated with the lower heat capacity of finer yarn assemblies. A smaller yarn diameter increases the surface-area-to-volume ratio, enabling faster heat exchange with the environment. In contrast, changing the ply number produced only a limited effect on response time. This suggests that adding parallel conductive filaments influences electrical pathways more than it alters the overall thermal inertia of the fabric system.

Thermal cycling results further highlight the structural influence of the weave. Resistance drift remained below 1.5% for all configurations, indicating acceptable repeatability of the conductive network. However, plain weave samples consistently showed slightly lower drift than their twill counterparts. The higher interlacement density in plain fabrics likely restricts yarn mobility during thermal

expansion and contraction, thereby stabilizing contact resistance between conductive segments. Twill structures, with their longer floats, may allow minor internal rearrangements under repeated heating and cooling, which could explain the slightly higher drift values observed.

Yarn fineness also appeared to influence long-term stability. Finer yarn configurations showed marginally greater drift, possibly because smaller filaments are more sensitive to subtle structural shifts or localized stress during thermal cycling. Conversely, two-ply yarns demonstrated slightly improved stability compared to single-ply yarns. The presence of parallel conductive filaments likely introduces a degree of electrical redundancy, reducing the impact of localized contact variations on overall resistance.

Taken together, the results indicate a clear trade-off between response speed and structural stability. Twill weaves provide faster thermal adaptation due to their more open structure and reduced compaction, whereas plain weaves offer greater resistance stability under repeated thermal loading. This balance suggests that weave architecture should not be selected arbitrarily in textile-based temperature sensors; rather, it should be aligned with the intended application. Systems requiring rapid thermal tracking may benefit from twill structures, while applications prioritizing long-term stability may favor plain weaves.

V. CONCLUSION

This work demonstrates that the thermal performance of woven temperature sensors can be meaningfully controlled through textile structural design rather than material modification alone. Among the investigated parameters, weave architecture played the most decisive role. Twill structures provided faster thermal response due to reduced interlacement density and improved heat transfer, whereas plain weaves offered slightly greater stability under cyclic thermal loading. Yarn linear density influenced response speed to a lesser extent, with finer yarns showing marginally faster equilibration, while ply number primarily affected electrical stability rather than thermal dynamics.

Overall, the results reveal a practical trade-off between response speed and long-term stability. These findings provide a structural design framework for tailoring woven temperature sensors according to specific application requirements, whether rapid temperature tracking or enhanced cyclic durability is prioritized.

This study focused solely on thermal response by varying structural properties of woven sensor. In future mechanical response can also be studied to explore the usage of woven sensor for multifunctional response.

ACKNOWLEDGMENT

This research was supported by the PhD research grant from NED University of Engineering and Technology. The authors gratefully acknowledge the institutional support provided for laboratory facilities and experimental work.

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