Pakistan Journal of Life and Social Sciences
www.pjlss.edu.pk

https://doi.org/10.57239/PJLSS-2026-24.2.023

RESEARCH ARTICLE

Thermal Fabrics Can Be Used as a Non-Invasive Visual Indicator to Monitor an Athlete's Physiological State During Training and Competitions

Seham M. Khan[1*], Nagwa T. Elsharawy[2]

[1,2]Department of Movement Science & Health, College of Sport Science, University of Jeddah, Saudi Arabia

[2] Department of Food Hygiene, Faculty of Veterinary Medicine, New Valley University, Egypt

ARTICLE INFO

Received: SEP 15, 2026

Accepted: OCT 8, 2026

Keywords

Metabolic Heat Production, Visual Detection, Exercise, Athlete Thermal Status, Skin Temperature Increase, Thermochromic Color Change

Corresponding Author:

dr.nagwa2000@gmail.com

ABSTRACT

Thermochromic textiles have emerged as an innovative class of passive smart materials capable of changing color in response to temperature variations without requiring electronic components or external power sources. Their ability to provide immediate visual feedback makes them promising candidates for non-invasive monitoring of athletes' thermal status during training and competition. This review presents a comprehensive overview of thermochromic textiles for sportswear applications, beginning with the physiological basis of human thermoregulation, including metabolic heat production, core and skin temperature regulation, heat dissipation mechanisms, and exercise-induced heat stress. The review discusses the fundamental principles of thermochromism, including reversible and irreversible systems, molecular mechanisms, transition temperatures, response time, hysteresis, and cycling stability. Various thermochromic technologies, including leuco dyes, cholesteric liquid crystals, microencapsulated pigments, thermochromic fibers, polymer-based materials, phase-change materials, and hybrid nanocomposites, are critically compared with respect to their thermal response, durability, and suitability for sportswear. The effects of environmental conditions, textile substrate properties, and garment construction on thermochromic performance are also examined, together with challenges related to washing resistance, ultraviolet stability, mechanical abrasion, and long-term color durability. Current evidence indicates that thermochromic textiles should be considered complementary passive visual indicators rather than replacements for electronic physiological monitoring systems. Future developments integrating advanced thermochromic materials with artificial intelligence, smartphone-based image analysis, and hybrid wearable technologies are expected to enhance monitoring accuracy and facilitate the development of next-generation intelligent sportswear for improving athlete safety, thermal comfort, and sports performance.

INTRODUCTION

Thermal homeostasis and athletic performance are closely related because exercise results in the production of excess body heat. If this excess body heat is not dissipated, body temperature will continue to rise. This can lead to a negative impact on performance and potentially cause dehydration, heat exhaustion, and heat stroke. For these reasons, the continuous monitoring of an athlete's thermal status has become important to an interdisciplinary approach to prevent injury

and improve performance. The recent development of technology that can be worn has greatly enhanced the ability to monitor an athlete's physiology (Islam, et al., 2025).

Monitoring can now be done on heart rate, respiration, muscle activity, the composition of sweat, and body temperature. The development of electronic textiles that integrate flexible sensors can be used for health and performance monitoring in a “real-time” manner and provide the athlete with comfort and the ability to move freely. Unfortunately, most systems that use flexible sensors are still electronic, which increases system complexity, manufacturing costs, maintenance needs, and the potential for unreliable performance during prolonged use in athletic performance.

In thermochromic materials, thermochromic pigments or dyes are their colour change involves selective absorption and/or scattering of responsible for the colour change. The terms *dye* and *pigment* are often light. Their colour properties depend on their chemical structure and use interchangeably, but they differ in many features, mainly in (i) physical characteristics of their particles, and their colour change may their chemical composition, (ii) behavior in medium, (iii) the be reversible or irreversible. Furthermore, thermochromic pigments (Jaszczak-Kuligowska, et al., 2026).

Passive smart textiles are an exciting developing alternative that, as their name suggests, interact with the environment around them or with the wearer without requiring electronic circuitry. They also include response textiles that engage in research activities with them. Thermochromic textiles, for instance, are a prime example of response textiles that have seen increased interest in research activities. They respond to temperature changes by changing their color. Thermochromic pigments are also optical response materials. They employ micro-encapsulation, leuco dyes, or liquid crystal systems, which are combined with textile fibers, coatings, or printing systems to retain reasonable flexibility and comfort of wear. Because of all these factors, the use of thermochromic textiles in ways to incorporate temperature indication within the textile itself is an excellent research area (Qiucheng, et al., 2026).

Thermochromic textiles are fundamentally different from other textile wearables, which rely on external circuitry for their operation. They, for example, do not require power supplies to function and are inherently lightweight and inexpensive. Since these features are essential for efficient sportswear, thermochromic textiles are perfectly suited for this application. Even more favorable is the development of reversible thermochromic textiles that now sport enhanced characteristics of tailoring to the needs of an application for wearable temperature monitoring (Dejene, Bekinew, 2025).

Even with these advancements, the use of thermochromic textiles in athletics is still quite new. Most studies focus on the fabrication of thermochromic textiles, the mechanisms of color transition, and printing methods. Studies of smart textiles have focused on the interaction of textiles and electronics, leaving large gaps where the potential use of smart textiles to assist the

monitoring of athletes' physiological responses to exercise remains unexplored. The use of thermochromic textiles to monitor thermoregulation, heat stress, and other exercise-related changes to physiological state also remains largely unexplored. Many hurdles remain with the use of thermochromic textiles, including the persistence of color changes, the transition temperature of the thermochromic dye, and the effects of the environment on the thermochromic textiles (Nursyafawani, et al., 2025).

The use of thermochromic textiles in sportswear aligns with advances in athlete monitoring technology that are non-invasive, less expensive, and easier for the athlete to use. Smart textiles will not replace traditional physiological sensors but may be used as passive displays that illustrate the skin temperature of an athlete, thus communicating the athlete's thermal state and the potential for thermal stress without the need for electronic components (Lale Civan & Semra Kurama, 2023 and Anurag Yadav & Kusum Yadav; 2025).

This review covers the use of thermochromic textiles in the design of sportswear. This review will also include the mechanisms of thermochromism, the various types of thermochromic materials, methods in the fabrication and integration of textiles, and the thermochromic textiles and their subsequent temperature-response behaviors and applications in sports and physiological monitoring. This review also analyzes the potential of these textiles as non-invasive means to visualize an athlete's physiological state. Within this context, the technological limitations of these fabrics and the potential directions for further research, including the integration of artificial intelligence, the use of smartphone-enabled color detection, multi-modal wearables, and next-generation Passive Smart Thermochromic Textiles will be discussed.

Human Thermoregulation during Exercise

Human thermoregulation is a process that allows the body to sustain its temperature when faced with changes in the environment and in bodily functions. The body can effectively maintain temperature. However, exercise poses challenges to this system. The efficiency of skeletal muscles is only around 20-25 % when exercising. Figure (1) shows the different thermochromic sports clothes, which indicate that around 75-80% of the body's energy is given off as heat. This increases the body's heat storage. Without the implementation of thermoregulation, exercising also poses challenges to cognitive function and safety. This is why exercise-induced thermoregulation must be understood before smart textiles that monitor thermal status are realized (Jaafar Y. and Dolaana K., 2025).

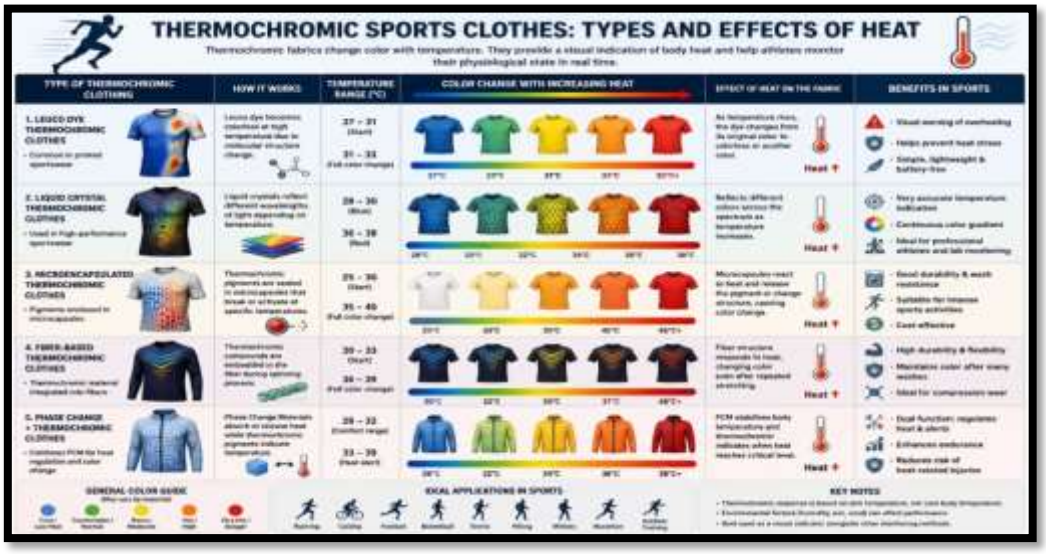


Figure (1): Thermo chromic Sports Clothes

Heat Production During Exercise

Heat arises primarily from the activity of contracting skeletal muscles, which use both aerobic and anaerobic metabolism. The amount of metabolic heat generated is determined by the exercise intensity and duration, muscle mass involved, environmental conditions, insulation from clothing, and individual characteristics such as body composition and aerobic fitness. During high-intensity exercise, metabolic heat production can increase more than 15-fold above resting levels. If heat dissipation is inadequate, this will lead to a progressive increase in body heat storage. High heat and humidity in the environment also contribute to thermal strain by limiting the body's ability to dissipate heat to the environment (Chithramol and Shine, 2023).

Core Temperature

Core body temperature (T_core) is the temperature of deep tissues and vital organs such as the brain, heart, and abdominal organs and is the main regulated variable of the human thermoregulatory system. Normal core temperature is maintained at about 36.5–37.5°C at rest, but there are individual and circadian variations. With prolonged or intensive exercise, metabolic heat production exceeds heat loss and core temperature usually rises to 38–39°C. Transient core temperatures exceeding 40°C have been observed in elite endurance athletes without clinical evidence of exertional heat illness, indicating that the absolute temperature does not always correlate with physiological risk. Instead, risk of heat-related illness is a function of the interplay of exercise intensity, environmental conditions, hydration status and individual heat tolerance (Islam, et al., 2023).

Temperature of Skin

Unlike core temperature, skin temperature is quite dynamic and responds rapidly to the environment and cutaneous blood flow. The average skin temperature is generally between 30 and

35 °C, depending on the ambient temperature, clothing, airflow and the intensity of exercise. During exercise, peripheral vasodilation increases blood flow to the skin, providing a means for heat transfer from the body core to the skin surface for dissipation. Because thermochromic textiles are in direct contact with the skin, they respond primarily to skin temperature rather than core temperature, and therefore an understanding of skin thermal physiology is particularly important when assessing their potential as passive temperature indicators (Avci, et al., 2024).

Evaporation of Sweat and Heat Loss

The human body loses heat by four main mechanisms as shown in figure (2): radiation, convection, conduction, and evaporation. During exercise in temperate environments, sweat evaporation is the primary cooling mechanism, accounting for most heat loss. When the core and skin temperatures increase, thermoreceptors are stimulated and send a signal to the hypothalamus to induce sweating. Eccrine sweat glands secrete sweat onto the surface of the skin. As sweat evaporates, latent heat is drawn away from the body, reducing skin and ultimately core temperature (Xu, et. al., 2023).

The efficiency of evaporative cooling depends on many external factors including ambient temperature, relative humidity, air velocity, and clothing characteristics. In high humidity, evaporation is greatly reduced because the vapor pressure gradient between the skin and the surrounding air is reduced. Clothing that is impermeable or highly insulated reduces moisture transport and increases heat storage. Hence, garment design is important to regulate thermal comfort and to prevent excessive physiological heat strain during athletic performance (Notley, et al., 2023).

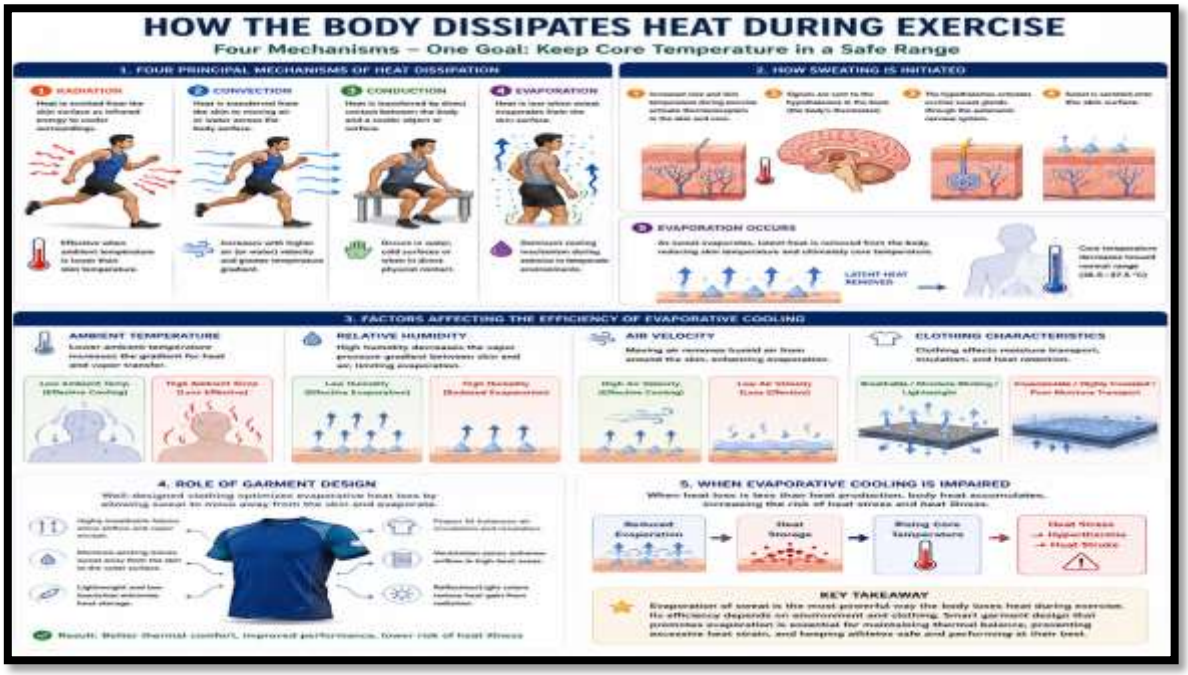


Figure (2): Heat Evaporation During Exercise

Exercise Heat Stress

Exercise heat stress is the progressive storage of body heat when the body cannot dissipate heat as quickly as metabolic heat is produced. Internal factors affecting heat stress include exercise intensity, hydration status, fitness level, and acclimatization, whereas external factors include ambient temperature, humidity, solar radiation, and clothing insulation. In moderate environmental conditions, prolonged or repeated bouts of high-intensity exercise can produce significant thermal strain. Recent systematic reviews indicate that hyperthermia is a frequent event in competitive and intermittent sports. This reinforces the fact that thermal stress is not limited to endurance events conducted in extreme heat (Rida, et al., 2023 and Van den Berghe, 2024).

Hyperthermia and Exertional Heatstroke

Hyperthermia is an abnormal increase in body temperature resulting from excessive heat storage when thermoregulatory processes are unable to maintain heat balance. Mild to moderate exercise-induced hyperthermia may be a normal physiological response and is commonly seen in competitive sport. However, extended elevation in core temperature can affect neuromuscular function, cardiovascular performance, decision making, and exercise capacity (Yeargin, et al., 2020 and Pryor et al., 2023).

Exertional heat stroke (EHS) is the most serious form of heat illness, and is a life-threatening medical emergency characterized by severe hyperthermia with central nervous system dysfunction including confusion, collapse, change in consciousness, or coma. Traditionally, a core temperature ≥40°C has been used as a diagnostic threshold, but recent evidence suggests that temperature alone is not sufficient for diagnosis, as some highly trained athletes may transiently exceed this value without developing clinical symptoms. Therefore, physiological monitoring should include both thermal measurements and clinical observations to accurately identify at-risk athletes (Sorensen & Hess,2022 and Sanchez-Botero, et al., 2023).

Physiological Temperature Ranges Safe for the Athlete

To interpret temperature-responsive sportswear, as declared in figure (3), it is important to know normal physiological temperature ranges. The normal core temperature at rest is between 36.5 and 37.5 °C, while the temperature of the skin normally varies between 30 and 35 °C, according to environmental conditions. With moderate exercise, the core temperature typically rises to 38–39°C, which is a normal adaptive response to increased metabolic heat production. Values approaching 39.5–40°C represent significant physiological heat strain, particularly if accompanied by dehydration or high environmental heat loads. Temperatures above 40°C should be carefully assessed clinically due to the increased risk of exertional heat illness. Because thermochromic textiles respond to changes in skin temperature rather than core temperature, transition temperatures should ideally correspond to physiologically meaningful skin temperature ranges

associated with increasing thermal strain during exercise. This concept provides the physiological basis for thermochromic sportswear development with the ability to serve as a non-invasive visual indicator of the athlete's thermal state (Yermakova, et al., 2022 and Wang, et al., 2023).

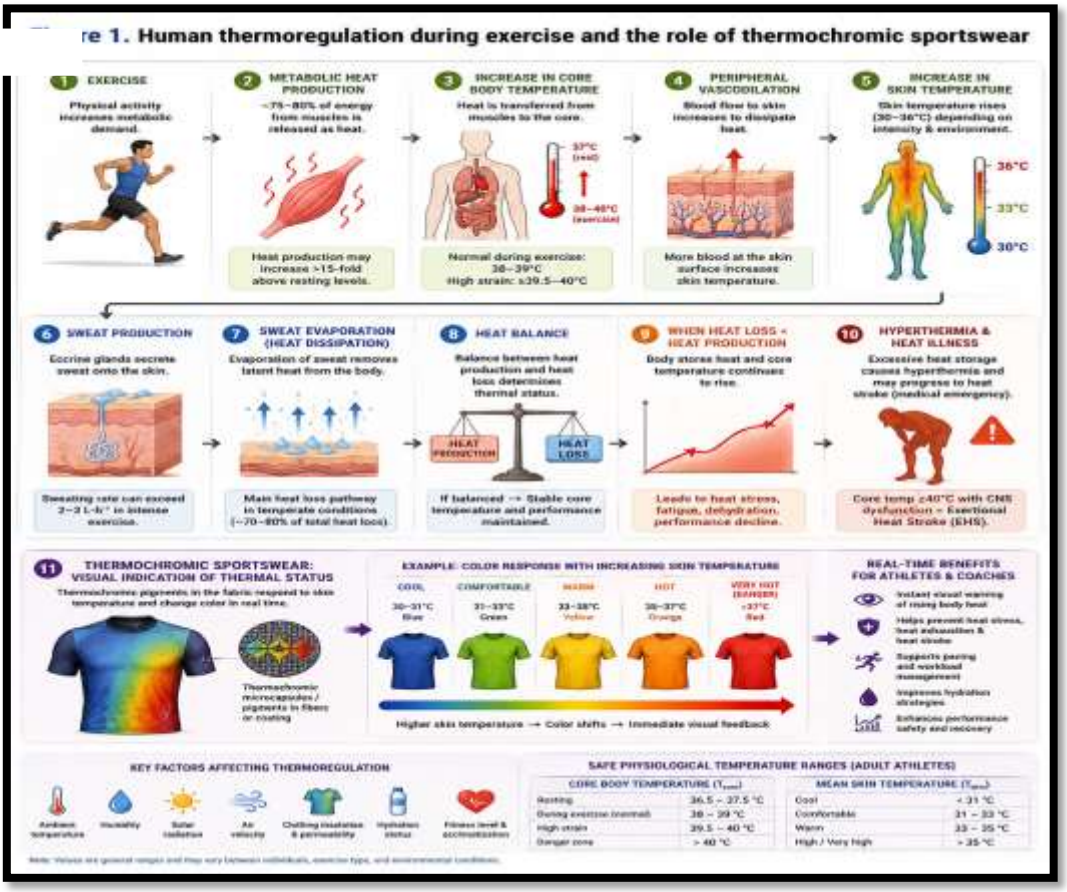


Figure (3): Human Thermoregulation During Exercise

Fundamentals of Thermochromism

What is Thermochromism?

Thermochromism is a change in optical properties (especially color) of a material in response to temperature change, either reversible or irreversible. The phenomenon is due to changes in the molecular structure, crystal ordering, or electronic energy states of the material, which affect the wavelength of reflected or absorbed visible light. Thermochromic materials have attracted enormous interest in recent years, owing to their passive and energy-free visual response to thermal stimuli, without the requirement of electronic sensors or external power sources. These features have made their use possible in fields such as smart packaging, temperature indicators, biomedical devices, security printing, energy-efficient buildings and, most recently, wearable textiles and smart sportswear (Magdalena et. al., 2024).

In textile engineering, thermochromic compounds are embedded into fabrics by printing, coating, microencapsulation, fiber spinning, or nanocomposite fabrication. The embedded thermochromic material undergoes a reversible optical transition with the change in fabric temperature, affording

an immediate visual indication of the local temperature change. In contrast to conventional wearable sensors that require electronics and data processing, thermochromic textiles provide intuitive visual feedback on the garment surface, making them attractive candidates for passive physiological monitoring during athletic activities (Hakami, et al., 2022 and Supian, et al., 2024).

Reversible and Irreversible Thermochromism

Thermochromic materials can be categorized as reversible or irreversible systems according to whether the original color can be recovered after cooling.

Thermochromism (Reversible)

Reversible thermochromic materials regain their original color when the temperature falls below the transition point. This behavior is caused by reversible molecular rearrangements, phase transitions, or equilibrium changes in the thermochromic system. Reversible materials dominate textile applications, permitting continuous monitoring under repeated heating and cooling cycles. The most widely used reversible systems are microcapsules containing leuco dyes, cholesteric liquid crystals, and some metal coordination complexes. Reversible thermochromism is of particular benefit for sportswear applications, as the clothing is heated under exercise and cooled during recovery phases, requiring multiple thousands of reversible thermal cycles without significant degradation (Jia, et al., 2022 and Royal Society of Chemistry, 2024).

Irreversible Thermochromism

Irreversible thermochromic materials undergo permanent chemical changes after exposure to a critical temperature. The color change is irreversible upon cooling because the molecular structure has been chemically altered. These materials are widely used in thermal history indicators, sterilization monitoring, food safety labels, and overheating detection, yet they are generally not suitable for reusable sports garments due to their one-time response. Currently, the research on smart sportswear mainly focuses on reversible thermochromic technologies (Lv , et al., 2022 and Guo & Zhang, 2024).

The Molecular Basis of Thermochromism

Several molecular mechanisms, depending on the material system used, induce thermochromic behavior. Leuco Dye Systems Leuco dye thermochromism is based on a three-component system of: Leuco dye, color developer, and organic solvent. In the limit of low temperature, the solvent is in a solid state, and the dye forms strong interactions with the developer, leading to the colored state. When the temperature is reached at which the solvent melts, molecular interactions are broken, and a colorless or differently colored state is produced. Cooling reverses the process and restores the original color. Leuco dyes remain the leading thermochromic technology for commercial textile applications due to their low manufacturing cost, flexibility, and ease of printing (Diptiman, et al., 2025).

Liquid Crystals Systems

Cholesteric liquid crystals are thermochromic because they change the pitch spacing of the molecules. The temperature changes the helical arrangement of the liquid crystal molecules, which changes the wavelength of the reflected light according to Bragg reflection. Liquid crystals do not switch between two colors but exhibit continuous spectral transitions: Blue > Green > Yellow > Orange > Red. These materials give very good resolution of temperature (about ±0.1°C), but they are more expensive and mechanically fragile compared to leuco dyes (Hossain, et al., 2023).

Thermochromism of Metal Complexes

Electronic transitions in transition-metal coordination compounds are temperature dependent due to ligand field changes or spin-state changes. It has been shown that these materials have excellent thermal stability, but their limited flexibility and difficulties in processing hinder their widespread use in textiles (Groeneveld, et al., 2023).

Polymer Based Thermochromic Systems

Recent studies have introduced thermochromic polymers and hydrogel systems that change their molecular conformation with temperature, as mentioned figure (5). These systems often exhibit improved flexibility, durability, and compatibility with wearable textiles, making them promising candidates for next-generation smart garments (Sharifi et al., 2024).

Temperature Range of Transition

The transition temperature (T_t) is one of the most important properties of thermochromic materials, and it is the temperature range in which the visible colour change takes place. Thermochromic materials don't work like normal temperature sensors that provide exact numerical readings but respond to temperature within certain ranges. Some typical ranges for transitions are as follows: Thermochromic material of Leuco dyes is Typical transition temperature at 20–70°C, and Thermochromic material of Liquid crystals is Typical transition temperature at 25–40°C, while Thermochromic material of Microencapsulated pigments is Typical transition temperature at 20–65°C. For sportswear, temperatures between 30–37 °C are optimal, since these temperatures are very close to physiologically relevant skin temperatures measured during exercise. Choosing inappropriate transition temperatures may lead to either premature color changes during resting conditions or failure to detect clinically relevant thermal stress (Isaiah, et al., 2022).

Hysteresis of Color

Color hysteresis is the difference between the heating and cooling transition temperatures. The temperature at which the colour disappears on heating should ideally be the same as that at which it appears on cooling. In practice, however, many thermochromic systems show hysteresis because of kinetic delays associated with phase transitions or molecular rearrangements. High values of

hysteresis may reduce the reliability of the measurement, since the same temperature may lead to different colors depending on the previous thermal history. Recent advances in microencapsulation and polymer chemistry have greatly reduced hysteresis, improved repeatability, and made thermochromic textiles more suitable for wearable sensing applications (RSC Advances, 2024 and Malte et al., 2025).

Time of Reaction

The response time is the duration for a thermochromic material to complete its optical transition after a temperature change is applied. The response time depends on many factors including particle size, thermal conductivity, thickness of the coating, textile architecture, air penetration, moisture levels, and environmental conditions. Nowadays, thermochromic paints usually react within a few seconds, or less than one second, and it is possible to visualize changes in skin temperature during physical activity almost in real time. Fast response is particularly important for sportswear, because body temperature can vary significantly during interval training, sprinting, or resting periods (Mousavi , et al., 2023 and Olyanasab & Annabestani 2024).

Cycling Stability and Reversibility

For wearable sports applications, the thermochromic materials need to have stable optical performance in thousands of heating–cooling cycles. The cycling stability is commonly evaluated by measuring: phase change temperature, color intensity, turnaround time, hysteresis, washability, and UV resistance. Repeated washing, exposure to ultraviolet radiation, perspiration and mechanical stretching can gradually degrade the thermochromic performance, by damaging the pigment microcapsules or changing the polymer matrices. Recent advances in nanocomposite coatings, polyurethane encapsulation, silicone binders and graphene-reinforced matrices have greatly improved durability while maintaining reversible color transitions, an important stride towards commercial smart sportswear (Kılıç, 2023).

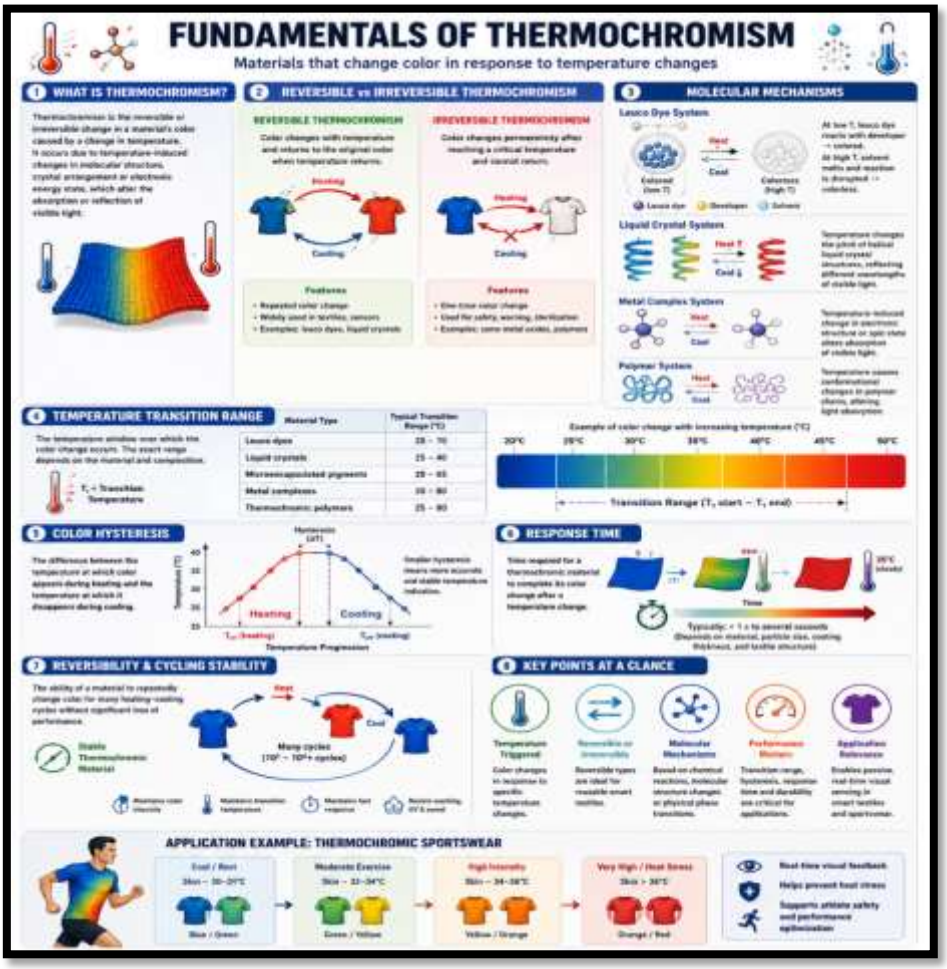


Figure (4). Fundamentals of Thermochromism and Temperature-Responsive Color Change in Smart Sportswear

Factors Affecting the Performance of Thermochromic Sportswear

The performance of thermochromic sportswear is not only affected by the characteristics of thermochromic materials themselves, but also by environmental conditions affecting the heat transfer between the human body and the surrounding atmosphere. Because thermochromic textiles are mainly sensitive to the surface (skin) temperature, any environmental factor that can alter heat exchange from the skin can alter the onset, magnitude, and duration of color change. Thus, knowledge of the effect of environmental conditions on the thermal behavior of textiles is important for understanding the thermochromic color changes of textiles during physical activity (Xiangkui and Fan, 2026).

Temperature of the Environment

Ambient temperature is one of the most influential environmental parameters on the performance of thermochromic textiles. As the environmental temperature rises, the temperature gradient between the skin and the surrounding air decreases, and so does convective and radiative heat loss. As shown in figure (5), the increase in skin temperature is more rapid, thus activating the thermochromic pigments more quickly. In contrast, cold environments increase heat dissipation

and slow down color transition even with similar amounts of metabolic heat generation. Thus, the thermochromic responses might be different for the same exercise intensities in different climatic conditions (Wu, et al., 2023 and Guo, et al., 2025).

For sportswear applications, the transition temperatures should be carefully selected depending on the expected environmental conditions. For example, clothes for marathon runners in hot climates require higher transition temperatures than clothes for winter sports. Experimental studies in recent years have shown that ambient temperature significantly affects the apparent sensitivity and response accuracy of thermochromic textiles, suggesting the importance of environmental calibration in wearable temperature monitoring (Zhou, et al., 2023 and Feng, et al., 2024).

Humidity (Relative)

Evaporative cooling is the main mechanism by which the body dissipates heat during exercise and is highly influenced by relative humidity. Sweating works well in low humidity as sweat evaporates taking latent heat from the skin limiting increases in skin temperature. High humidity, on the other hand, impairs evaporation by reducing the vapor pressure gradient between the skin and the surrounding air, leading to higher skin temperature for the same level of sweat production. For thermochromic sportswear, this effect may lead to quicker colour changes under humid conditions, which may indicate higher physiological heat strain, and not just higher exercise intensity. Humidity should always be considered in the interpretation of thermochromic colour changes in outdoor sports (He, et al., 2023 and Wang, et al., 2024).

Solar Irradiance

The solar radiation adds directly to the heating of the garments, in addition to the metabolic heat production. Dark colored textiles absorb much more solar energy than light colored fabrics, which may increase the fabric surface temperature above the true skin temperature. Thus, thermochromic textiles exposed directly to sunlight may show premature or enhanced colour changes even if the physiological heat stress is still moderate. Recent studies have proposed reflective coatings, infrared-blocking nanoparticles, or UV-resistant outer layers to mitigate solar-induced measurement errors in outdoor athletic applications (He, et al., 2023).

Wind Speed

The wind enhances convective heat transfer and the sweat evaporation rate, and therefore body cooling. In activities like cycling, marathon running, and skiing, increased airflow significantly lowers skin temperature, delaying thermochromic activation. On the other hand, low air movement means less convective cooling, so heat can accumulate under clothing. The effect of wind is especially important in porous sport fabrics where increased ventilation can lead to a faster decrease in local fabric temperature than skin temperature. Therefore, in designing thermochromic clothing for outdoor sports, the air velocity should be considered (Mlawer, et al., 2024).

Rain and Dampness

Rain adds complexity because liquid water changes the thermal properties of textiles and also cools the garment through conductive heat transfer. Moisture can also change the light scattering in textile fibers, which can affect the optical properties of thermochromic pigments. Some microencapsulated thermochromic pigments will lose color intensity when saturated with water, though advanced waterproof encapsulation systems can provide relatively stable color performance. Water resistance is thus an important consideration in designing thermochromic clothing for endurance sports and outdoor activities (Wu, et al., 2023).

Thickness of the Fabric

Fabric thickness is directly related to the thermal insulation and heat transfer between the skin and the external environment. Thin fabrics respond thermochromically faster but also equilibrate with skin temperature faster. Contrarily, the thick multilayer textiles hinder the heat conduction, so the response time increases and the temperature sensitivity decreases. However, increasing thickness might improve thermal stability by reducing the effect of short-time fluctuations in the environment. Thus, the design of thermochromic sportswear should aim for a balance between thermal responsiveness and environmental protection (Pakdel, X. Wang, 2023).

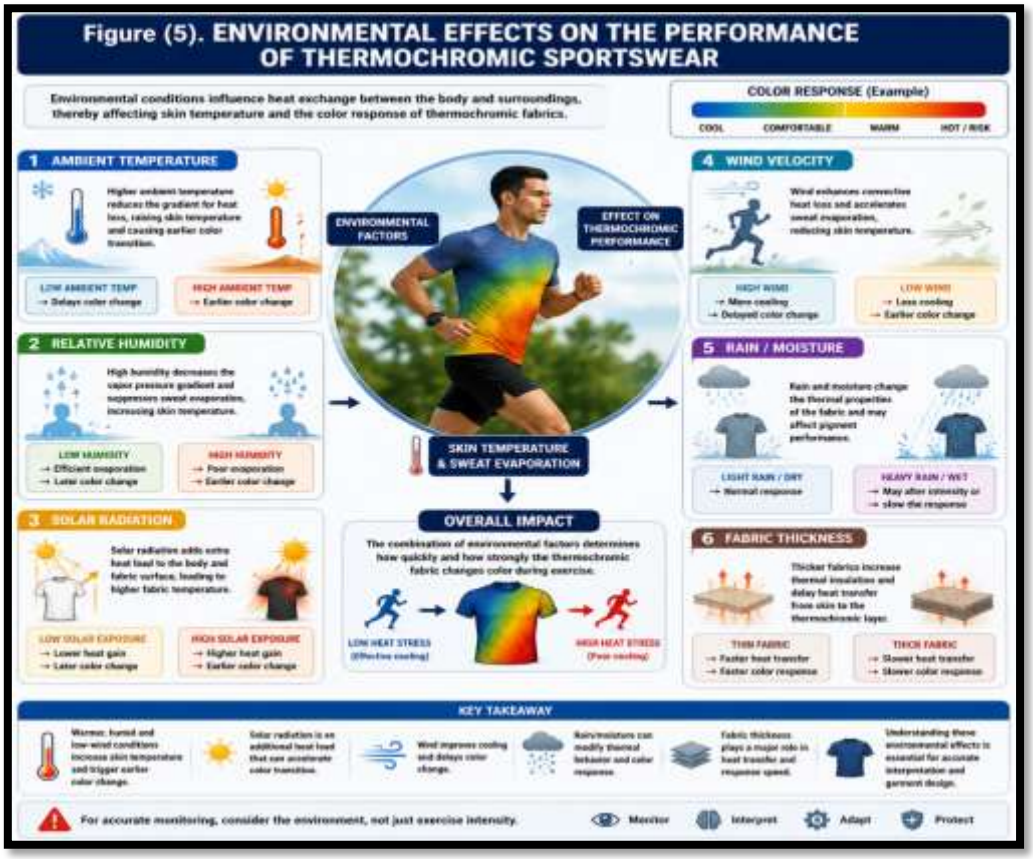


Figure (5). Environmental Effects on the Performance of Thermochromic Sportswear

Properties of Textile Affecting Thermochromic Performance

The thermal behavior, durability, flexibility, and overall sensing performance of thermochromic garments depend heavily on the choice of textile substrate. The heat transfer efficiency between skin and the thermochromic layer is determined by fiber composition, fabric architecture, moisture management, and mechanical properties in combination (Tözüm, et al., 2022 and Borhan, et al., 2024).

Cotton Clothing

Cotton fibers are comfortable to wear and can absorb a lot of moisture, but they are poor conductors of heat. The absorption of moisture causes a delay in temperature change within the fabric, resulting in thermochromic responses of cotton garments that are generally slower than those of synthetic textiles. With the following advantages: Breathable, Eco-friendly, while its limitations were: Superb Water Absorption, longer drying time, Thermal response slow (Adamu & Gao, et al., 2022 and Demirbağ-Genç, et al., 2025).

Polyester Fabrics

Polyester is the major fiber used in sportswear due to its low moisture regain, fast drying, dimensional stability, and great durability. The low moisture absorption allows for rapid thermal equilibration between the skin and the thermochromic layer, leading to faster color transitions. Polyester is also highly compatible with thermochromic printing technologies (Li, et al., 2022).

Nylon Fabrics

Nylons have higher thermal conductivity than polyester and have excellent mechanical strength and elasticity. It is well suited due to its flexibility to compress garments with thermochromic coatings. But nylon absorbs more moisture than polyester, which could impact thermal response during prolonged exercise (Kılıç, 2023).

Knitted Fabric

Knitted structures are made of interlocking loops that offer high elasticity, better air permeability, and better moisture transport. These features allow an efficient heat exchange between the skin and the thermochromic layer; thus, knitted fabrics are the best substrate for smart sportswear. Recent studies show that knitted thermochromic fabrics are more porous than woven structures and therefore respond faster (Eryuruk, et al., 2022).

Fabrics Woven

Woven fabrics are more dimensionally stable and less stretchy than knitted textiles. Their compact structure generally enhances the air permeability and thus the thermal insulation and the delay of thermochromic activation. However, woven fabrics are characterized by better printing quality and excellent mechanical durability (Štaffová, et al., 2020).

Compression Clothing

Compression garments ensure constant contact between the thermochromic layer and the skin, thus limiting the presence of air gaps that would otherwise reduce thermal transfer. Thus, compression sportswear usually shows in the table, (1), where the best reproducibility of measurements among textile systems. Such close skin contact may increase the reliability of visual temperature indication during athletic activity (Nursyafawani, et al., 2025).

Table (1). Textile systems comparison for thermochromic sportswear

Textile System	Moisture Management	Thermal Response	Comfort	Suitability
Cotton	Excellent absorption	Slow	Excellent	Moderate
Polyester	Excellent wicking	Fast	Excellent	Excellent
Nylon	Moderate	Fast	Very good	Very good
Knitted	Excellent ventilation	Very fast	Excellent	Excellent
Woven	Moderate	Moderate	Good	Good
Compression	Excellent skin contact	Fastest	Very good	Excellent

Thermochromic Textiles Durability

Practical thermochromic sportswear should be durable in the long term since the garments are repeatedly subjected to laundering, ultraviolet radiation, perspiration, stretching, and mechanical abrasion (Figure 6) (Izabela et al., 2026).

Washing Fastness

One of the main sources of thermochromic degradation is repeated laundering. Mechanical agitation, detergents, and high temperatures of washing may damage the pigment microcapsules or weaken the binder matrix, causing a reduction of the color intensity and an increase in the variability of the transition temperature. The washing durability of these systems has been greatly improved by recent advances in polyurethane and silicone-based encapsulation technologies, with some systems maintaining >80–90% of their original color intensity after 50 laundering cycles (Singh, et al., 2023 and Orjuela-Garzón, et al., 2024).

Stability in the Ultraviolet

Thermochromic pigments are prone to permanent photochemical degradation when exposed to UV radiation. UV exposure usually causes lower color saturation, higher transition temperature, slower response, and shorter service life. Modern UV absorbers, graphene coatings, titanium dioxide nanoparticles, and zinc oxide nanoparticles have been introduced to improve photostability (Naito, et al., 2023 and Hu, et al., 2025).

Mechanical Abrasion

Athletic clothes are always in friction during running, cycling, and repeated body movement. Mechanical abrasion or removal of printed layers can break thermochromic microcapsules and result in decreased optical performance. Recent developments in flexible polymer binders and

nanocomposite coating have greatly enhanced abrasion resistance while maintaining fast color response (Lee, et al., 2023 and Catrysse, & Fan, 2024).

Long-Term Color Stability

The Long-term performance is dependent on consistent transition temperature, response time, and color intensity over repeated heating-cooling cycles. When properly encapsulated, the present high-performance thermochromic systems have shown stable performance for thousands of thermal cycles. Future research should focus on environmentally sustainable encapsulation materials, enhanced photostability, and standardized durability testing protocols specific to smart sportswear (Singh, et al., 2023 and Lianget al., 2024).

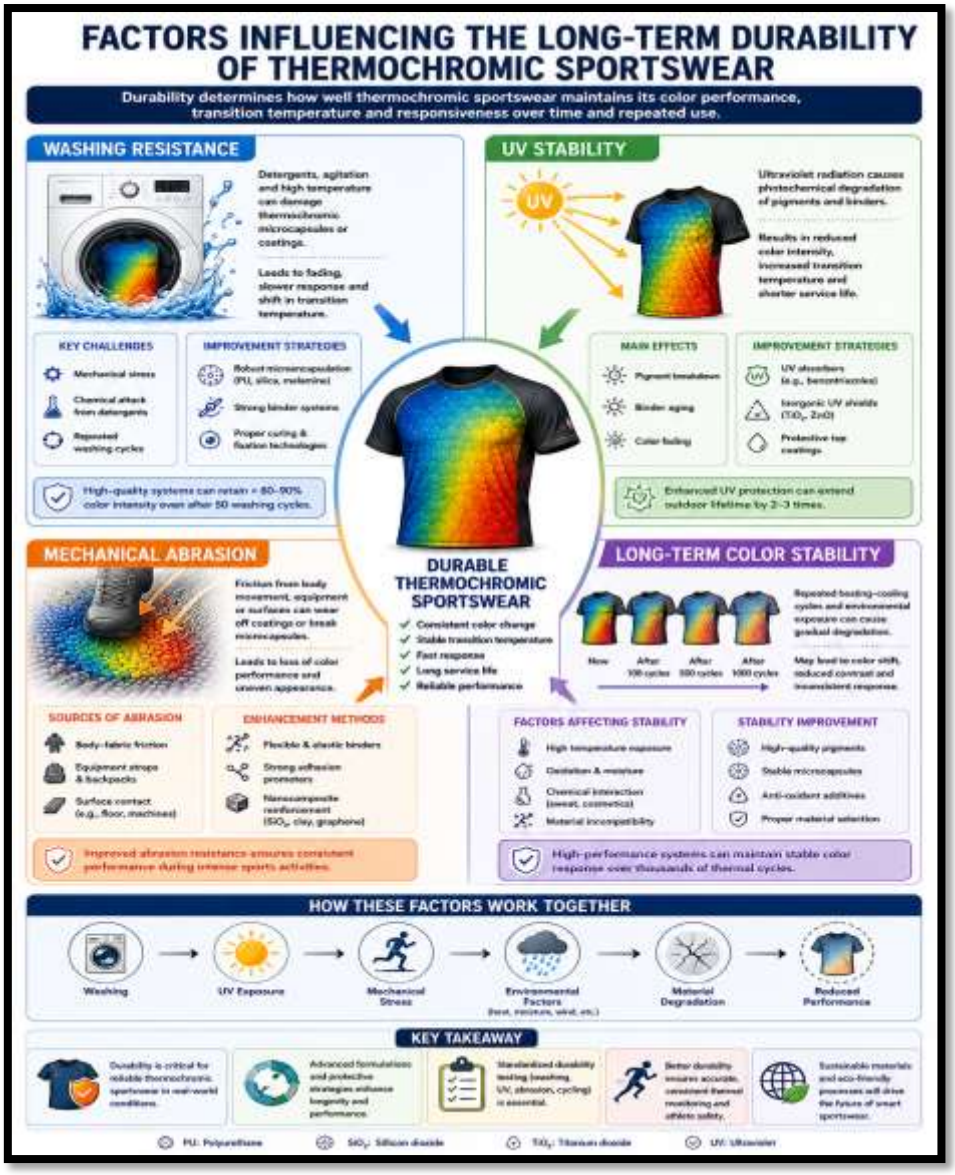


Figure (6). Factors in Influencing the Long-term Durability of Thermochromic Sportswear

CONCLUSION

Thermochromic textiles are a promising class of passive smart materials that can provide real-time visual responses to temperature variations without requiring electronic components or external power sources. The review covered the basic concepts of thermochromism, such as reversible and irreversible systems, molecular mechanisms, temperature-transition behavior, hysteresis, response time, and cycling stability, as well as their incorporation into sportswear applications. Among the technologies available, leuco dye systems are still the most suitable for wearable textiles due to their low cost, flexibility, and compatibility with conventional textile manufacturing. Liquid crystal systems offer higher temperature sensitivity but are limited by their complexity and durability issues. The review also pointed out the impact of environmental conditions (ambient temperature, humidity, solar radiation, wind, rain, and fabric thickness) on thermochromic performance and stressed the need to take these factors into account when analyzing the color transitions during athletic events. The choice of textile substrate also determines the thermal responsiveness, moisture management, and wearer comfort, with polyester, knitted fabrics, and compression garments generally showing improved performance. Durability is a major issue because repeated washing, UV exposure, and mechanical abrasion can reduce colour stability and sensing reliability, even with recent advances in microencapsulation and protective coatings. In conclusion, thermochromic sportswear should not be considered as a substitute for electronic physiological monitoring systems, but as a complementary technology. Thermochromic clothing provides a lightweight, non-invasive, and convenient approach to monitoring the thermal state of athletes through the conversion of skin temperature changes into easy-to-interpret visual cues. Ongoing improvements in material engineering and textile design are expected to boost their reliability and facilitate their use in next-generation smart sportswear.

RECOMMENDATIONS

Future work should be aimed at improving the accuracy, durability, and practical applicability of thermochromic textiles in sportswear and physiological monitoring. First, transition temperatures should be optimized to represent physiologically meaningful skin temperature ranges encountered during exercise so that garments can distinguish between normal thermoregulation, moderate heat stress, and potentially hazardous conditions. Quantitative calibration methods correlating color change with skin temperature have to be developed as well to improve measurement reliability. We need standardized testing protocols for evaluating transition temperature, response time, hysteresis, wash durability, UV resistance, and mechanical performance in realistic sporting conditions. Material science innovations should aim at the development of highly durable thermochromic pigments, environmentally stable microencapsulation systems, multifunctional nanocomposites and sustainable bio-based materials that can be used multiple times. Integration with emerging digital technologies is also expected to benefit future thermochromic sportswear. Hybrid systems comprising thermochromic textiles integrated with wearable sensors, smartphone

image analysis, artificial intelligence and IoT platforms could deliver both qualitative visual feedback and quantitative physiological monitoring. Additional large-scale field studies with athletes of different sports and environmental conditions are needed to confirm laboratory findings and to develop practical guidelines for performance. Finally, personalized thermochromic clothing, based on individual physiological characteristics, sport-specific demands, and environmental conditions, can potentially offer a more precise thermal evaluation and help prevent injuries, optimize performance, and improve athlete safety. Such advances will allow the use of thermochromic textiles to evolve from simple color-changing materials to intelligent passive interfaces for next-generation wearable sports technologies.

REFERENCES

A.B. Avci, G.A. Balci, T. Basaran, Exercise and resting periods: thermal comfort dynamics in gym environments, in: Building Simulation, Springer, 2024.

Adamu, B.F.; Gao, J. Comfort-related woven fabric transmission properties made of cotton and nylon. Fash. Text. 2022, 9,

Anurag Yadav & Kusum Yadav (2025). Transforming healthcare and fitness with AI powered next-generation smart clothing. Discover Electrochemistry. 1-34.

Borhan, I.Z.; Nor Affandi, N.D.; Ab Kadir, M.I.; Yahaya, R.; Bonnia, N.N. Morphological analysis and thermochromism of combatfabric. Malays. J. Microsc. 2024, 20, 285–296.

C.-E. Hu, T.-Y. Wang, D.-S. Lin, M.-W. Chen, C.-W. Huang. Mie-optimized PMMA particles for fully polymer-based radiative cooling coatings with high reflectance and hydrophobicity. RSC Adv., 15 (2025), pp. 19104-19115, 10.1039/D5RA01834J

Color-Changing Materials (Royal Society of Chemistry). *Reversible thermochromic fibers with excellent washing durability*. **RSC Advances**, 2024.

Dejene, Bekinew (2025). The future of fabric: A comprehensive review of self-powered smart textiles and their emerging applications. Energy Reports. 14: 898-943

Demirbağ-Genç, S.; Tözüm, M.S.; Alay-Aksoy, S. A dual-function cotton fabric with thermochromic and thermoregulationproperties containing Floran dye-based gelatin/gum Arabic-walled thermochromic microcapsules. Res. J. Text. Appar. 2025, 29.[CrossRef]

E. Pakdel, X. Wang. Thermoregulating textiles and fibrous materials for passive radiative cooling functionality. Mater. Des., 231 (2023), Article 112006, 10.1016/j.matdes.2023.112006

E.J. Mlawer, J. Mascio, D.D. Turner, V.H. Payne, C.J. Flynn, R. Pincus. A more transparent infrared window. J. Geophys. Res. Atmos., 129 (2024), Article e2024JD041366,

Eryuruk, S.; Gidik, H.; Koncar, V.; Kalaoglu, F.; Tao, X.; Saglam, Y. Heat and moisture transfer properties of a firefighter clothing with a new fire-resistant underwear. J. Ind. Text. 2022, 51 (Suppl. S3), 4480S–4513S.

Groeneveld I., Kanelli M., Ariese F., van Bommel M.R. Parameters That Affect the Photodegradation of Dyes and Pigments in Solution and on Substrate—An Overview. Dyes Pigment. 2023;210:110999. doi: 10.1016/j.dyepig.2022.110999.

Guo S., Zhang A. Review of Different Temperatures for Biopreservation. Int. J. Refrig. 2024;157:53–59. doi: 10.1016/j.ijrefrig.2023.10.014.

H. Guo, H. Liu, Z. Wang, Y. Si, B. Wang. Advances in electrospun nanofiber materials for outdoor passive radiative cooling: a review Small Methods, 9 (2025), Article e01872, 10.1002/smtd.202501872

Hakami A., Srinivasan S.S., Biswas P.K., Krishnegowda A., Wallen S.L., Stefanakos E.K. Review on Thermochromic Materials: Development, Characterization, and Applications. J. Coat. Technol. Res. 2022;19:377–402. doi: 10.1007/s11998-021-00558-x.

Hossain S., Sadoh A., Ravindra N.M. Principles, Properties and Preparation of Thermochromic Materials. Mater. Sci. Eng. Int. J. 2023;7:146–156. doi: 10.15406/mseij.2023.07.00218.

I. Yermakova, L. Montgomery, A.W. Potter, Mathematical model of human responses to open air and water immersion: modeling human thermoregulatory responses, Journal of Sport and Human Performance 10 (1) (2022) 30–45.

I.C. Orjuela-Garzón, C.F. Rodríguez, J.C. Cruz, J.C. Briceño. Design, Characterization, and Evaluation of Textile Systems and Coatings for Sports Use: Applications in the Design of High-Thermal Comfort Wearables. ACS Omega, 9 (2024), pp. 49143-49162, 10.1021/acsomega.4c05600

Isaiah Di Domenico, Samantha M. Hoffmann1 and Paul K. Collins (2022). The Role of Sports Clothing in Thermoregulation, Comfort, and Performance During Exercise in the Heat: A Narrative Review. Sports Medicine - Open 8(58): 1-125. DOI:10.1186/s40798-022-00449-4

Islam Md Touhidul; Hosen Md Imran; Islam Tarikul; Almamun, Md. Abdullah; Islam Tariful (2025): Advancements in functional smart and wearable textiles for sportswear applications. Royal Society of Chemistry, 15: 50206-50232.

Izabela Jasińska, Alicja Nejman, Beata Tkacz-Szczęsna and Sandra Flinčec Grgac. Durability Assessment of Elastolefin-Based Workwear Fabrics. *Fibers* 2026, *14*(3), 35; https://doi.org/10.3390/fib14030035

J. Zhou, J. Zhao, X. Guo, Y. Hu, X. Niu, F. Wang. Personal wearable thermal and moisture management clothing: a review on its recent trends and performance evaluation methods Processes, 11 (2023), p. 3063, 10.3390/pr11113063

Jaafar Younes and Dolaana Khovalyg (2025). Advances in human thermophysiology modelling: Methodological review of a century of developments. Computers in Biology and Medicine. 198, Part B: 111218: (1-28).

Jaszczak-Kuligowska, Malwina; Sąsiadek-Andrzejczak, Elzbieta; Safandowska. Marta; Kozicki, Marek; Madiedo, Laura; Barburski, Marcin; Ranz, David; Mallada, Reyes (2026); Thermochromic textile sensors for temperature measurements. Measurement257, 118698: 1-16.

Jia Q.-Q., Luo Q.-F., Ni H.-F., Su C.-Y., Fu D.-W., Xie L.-Y., Lu H.-F. High-Sensitivity Organic–Inorganic Hybrid Materials with Reversible Thermochromic Property and Dielectric Switching. J. Phys. Chem. C. 2022;126:1552–1557. doi: 10.1021/acs.jpcc.1c10347. **3.2**

K. Feng, Y. Wu, X. Pei, F. Zhou Passive daytime radiative cooling: from mechanism to materials and applications Mater. Today Energy, 43 (2024), Article 101575, 10.1016/j.mtener.2024.101575

Kılıç, A. (2023). Research into the effects of pigment printing parameters on sensorial comfort to guide garment designers in the apparel industry. *Ind. Textila* **2023**, *74*, 310–320.

Kılıç, A. Research into the effects of pigment printing parameters on sensorial comfort to guide garment designers in the apparel industry. Ind. Textila 2023, 74, 310–320.

L. Liang, S. Bai, K. Lin, C.T. Kwok, S. Chen, Y. Zhu, C.Y. Tso. Advancing sustainable development: broad applications of passive radiative cooling. Sustainability, 16 (2024), p. 2346, 10.3390/su16062346

Lale Civan & Semra Kurama (2023). Preparation and characterization of intelligent thermochromic fabric coatings for the detection of fever diseases. Mater Chem Phys. 27; 305: 127977. doi: 10.1016/j.matchemphys.2023.127977

Li, W.; Yan, X.; Zhao, W. Preparation of crystal violet lactone complex and its effect on discoloration of metal surface coating. Polymers 2022, 14, 4443.

Lv L.-Y., Cao C.-F., Qu Y.-X., Zhang G.-D., Zhao L., Cao K., Song P., Tang L.-C. Smart Fire-Warning Materials and Sensors: Design Principle, Performances, and Applications. Mater. Sci. Eng. R. Rep. 2022;150:100690. doi: 10.1016/j.mser.2022.100690.

M. Chithramol, S. Shine, Review on modelling approaches of thermoregulation mechanisms, J. Therm. Anal. Calorim. 148 (17) (2023) 9343–9360.

M. Rida, A. Frijns, D. Khovalyg, Modeling local thermal responses of individuals: validation of advanced human thermo-physiology models, Build. Environ. 243 (2023) 110667.

M. He, B. Zhao, X. Yue, Y. Chen, F. Qiu, T. Zhang. Infrared radiative modulating textiles for personal thermal management: principle, design and application. Nano Energy, 116 (2023), Article 108821, 10.1016/j.nanoen.2023.108821

M. Lee, G. Kim, Y. Jung, K.R. Pyun, J. Lee, B.-W. Kim, S.H. Ko. Photonic structures in radiative cooling. Light Sci. Appl., 12 (2023), p. 134, 10.1038/s41377-023-01119-0

M.R. Islam, K. Golovin, P.I. Dolez, Clothing thermophysiological comfort: a textile science perspective, Textiles 3 (4) (2023) 353–407.

Magdalena Wilk-Kozubek, Bartłomiej Potaniec, Patrycja Gazińska, Joanna Cybińska (2024). Exploring the Origins of Low-Temperature Thermochromism in Polydiacetylenes. Polymers (Basel). 16(20):2856. doi: 10.3390/polym16202856

Malte Satow, Hein Daanen, Razan Wibowo, Stefan Rakete, Stephan Bose-O'Reilly, Daniela Koller (2025). Impact of summer heat on male children's physiological responses during football training. Environmental Research 286, 122725: 1-10.

Mousavi A, Rahimnejad M, Azimzadeh M, Akbari M, Savoji H. (2023). Recent advances in smart wearable sensors as electronic skin. J Mater ChemB. 11: 10332–54. https://doi.org/10.1039/D3TB01373A.

Nursyafawani Idris; Nor Dalila Nor Affandi; Intan Zulaikha Borhan; Muhammad Ismail Ab Kadir; Ridwan Yahaya; Liliana Indrie (2025). Thermochromic Behaviour and Comfort Properties of Printed Woven Fabric. Coatings, 15(6): 692-705. https://doi.org/10.3390/coatings15060692

Olyanasab A, Annabestani M. (2024). Leveraging machine learning for personalized wearable biomedical devices: a review. J Personal Med.14:203.

P.B. Catrysse, S. Fan. Radiative cooling textiles using industry-standard particle-free nonporous micro-structured fibers. Nanophotonics, 13 (2024), pp. 649-657, 10.1515/nanoph-2023-0650

Pryor RR, Haboian K, Fitts T, Stooks JJ. Tarp-Assisted Cooling for Exertional Heat Stroke Treatment in Wildland Firefighting. Wilderness Environ Med. 2023 Dec;34(4):490-497.

Qiucheng Lu; Xu Wang; Xiaohui Zhao; Ziqiang Bi; Hailin Li; Yuqing Liu (2026). Recent Advances in Reversible Thermochromic Materials for Smart Textiles: A Review. Materials (Basel). 14;19(4):742.

S. Singh, S. Kumar, V. Khanna. A review on surface modification techniques. Mater. Today. Proc. (2023), 10.1016/j.matpr.2023.01.010

S.R. Notley, D. Mitchell, N.A. Taylor, A century of exercise physiology: concepts that ignited the study of human thermoregulation. Part 1: foundational principles and theories of regulation, Eur. J. Appl. Physiol. 123 (11) (2023) 2379–2459.

Sanchez-Botero L, Agrawala A, Kramer-Bottiglio R. Stretchable, breathable, and washable fabric sensor for human motion monitoring.Adv Mater Technol. 2023;8:2300378. https://doi.org/10.1002/admt.202300378.

Sharifi M., Sharifi A., Abaee M.S., Mirzaei M. A Review on Fluoran Compounds as Widely Used Leuco Dyes. Dyes Pigment. 2024; 221:111783. doi: 10.1016/j.dyepig.2023.111783.

Sorensen C, Hess J. Treatment and Prevention of Heat-Related Illness. N Engl J Med. 2022 Oct 13;387(15):1404-1413.

Štaffová, M.; Kucera, F.; Tochacek, J.; Dzik, P.; Ondreáš, F.; Jancar, J. Insight into color change of reversible thermochromic systems and their incorporation into textile coating. J. Appl. Polym. Sci. 2020, 138, 49724.

Supian A.B.M., Asyraf M.R.M., Syamsir A., Najeeb M.I., Alhayek A., Al-Dala'ien R.N., Manar G., Atiqah A. Thermochromic Polymer Nanocomposites for the Heat Detection System: Recent Progress on Properties, Applications, and Challenges. Polymers. 2024;16:1545. doi: 10.3390/polym16111545.

T. Naito, T. Saito, M. Ohhashi, S. Hayashi. Recovery with a fan-cooling jacket after exposure to high solar radiation during exercise in hot outdoor environments. Front. Sports Act. Living, 5 (2023), 10.3389/fspor.2023.1106882

Tözüm, M.S.; Alkan, C.; Aksoy, S.A. Developing of thermal energy storing visual textile temperature indicators based onreversible color change. J. Ind. Text. 2022, 51, 1964S–1988S.

Van den Berghe P. A primer on wearable technology for injury risk management in distance running. In: Düking P, Sperlich B, editors.Individualizing training procedures with wearable technology. Berlin: Springer; 2024. p. 37–68.

Wang C, He T, Zhou H, Zhang Z, Lee C. Artificial intelligence enhanced sensors-enabling technologies to next-generation healthcareand biomedical platform. Bioelectron Med. 2023; 9:17.

X. Xu, T.P. Rioux, M.P. Castellani, Three-dimensional models of human thermoregulation: a review, J. Therm. Biol. 112 (2023) 103491.

X. Wu, J. Li, Q. Jiang, W. Zhang, B. Wang, R. Li, S. Zhao, F. Wang, Y. Huang, P. Lyu, Y. Zhao, J. Zh u, R. Zhang. An all-weather radiative human body cooling textile. Nat. Sustain, 6 (2023), pp. 1446-1454, 10.1038/s41893-023-01200-x

X. Zhang, F. Wang, H. Guo, F. Sun, X. Li, C. Zhang, C. Yu, X. Qin. Advanced cooling textiles: mechanisms, applications, and perspectives. Adv. Sci., 11 (2024), Article 2305228, 10.1002/advs.202305228

Xiangkui Kong, Cuihong Fan (2026). Materials engineering design of radiative cooling sports textiles and their emerging applications in outdoor athletics (Review). Alexandria Engineering Journal. 144: 117-128.

Y. Wang, B. Zhao, H. Zhu, W. Yang, T. Li, Z. Cao, J. Wang. Vests with radiative cooling materials to improve thermal comfort of outdoor workers: an experimental study. Nanomaterials, 14 (2024), p. 1119, 10.3390/nano14131119