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RECENT DEVELOPMENTS IN TEXTILE-BASED P^{H} SENSORS FOR NON-INVASIVE MEDICAL APPLICATIONS

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ABSTRACT

The pH levels in biofluids, including sweat, wound exudates, tears, and saliva, indicate hydration status, dermatological conditions, and underlying health issues such as kidney disease. The rapid development of wearable technology in health monitoring has led to considerable interest in textile-based wearable sensors, owing to their flexibility, comfort, breathability, biodegradability and diverse fabrication methodologies. Although there are numerous reviews on textile-based wearable sensors, a thorough review specifically addressing wearable textile-based pH sensors is lacking. The objective of this review is to present a comprehensive analysis of the current status of research on textile-based colorimetric pH sensors, highlighting their prospective applications in non-invasive health monitoring. Key textile substrates, pH-sensitive dyes, surface functionalization techniques, dye immobilization strategies, and innovative fabrication methods are discussed. Possible limitations of colorimetric sensors, including dye leaching, stability challenges, accuracy issues, and inadequate reversibility are summarized, and research initiatives aimed at improving sensor performance, durability, and wearability, such as encapsulation, multi-layer coatings, sol-gel methods, hydrogels, printing, chemical and physical bonding, and printing, are included. Besides, novel techniques such as nanofiber-based dye encapsulation and sensor miniaturization, and enhancement of sensor sensitivity, dye retention, and response time, are highlighted. This work will shed light on future development of textile-based pH sensors for wearable, non-invasive and reliable medical applications.

KEYWORDS: pH sensors; pH-sensitive dyes; colorimetric; medical; textiles

INTRODUCTION

Recent advancements in chemical sensor technology have significantly enhanced the potential for non-invasive analysis of readily accessible peripheral biofluids (Yang et al. 2010). Among key physiological parameters, pH serves as a potential biomarker reflecting the body's metabolic activity and homeostasis balance (Boeva et al. 2024). Deviations from normal pH levels may indicate underlying physiological conditions or disruption in physiological equilibrium (Wang et al. 2020; Xu et al. 2023).

In conventional clinical diagnostics, blood has been the primary medium for clinical pH measurements (Zhang et al. 2019). However, blood sampling is invasive, intermittent, and unsuitable for continuous real-time health monitoring (Pour et al. 2024; Mugo & Zhang 2019; McCaul, Glennon & Diamond 2017). In contrast, biofluids such as saliva, tears, and sweat offer promising non-invasive alternatives, that enable real-time physiological monitoring without professional medical intervention (Falk et al. 2020; Seshadri et al. 2019). The development of wearable chemical sensors has further enhanced the ability to continuously monitor such biofluids, allowing for the detection of ions like H_3O^+ and Na^+ in real-time (Bandodkar et al. 2019).

Among wearable sensing platform, non-invasive wearable sensors have gained increasing attention due to their ability to monitor physiological parameters without penetrating the skin barrier (Heng et al. 2022). These devices eliminate the need for surgical or semi-invasive procedures required for monitoring parameters such as blood glucose or cardiac biomarkers (Parlak et al. 2019). Instead, they can be seamlessly integrated into external devices like smartwatches, wristbands, and textiles, offering user comfort, safety and continuous monitoring and data acquisition (Heng et al. 2022). For reliable operation, wearable pH sensors must exhibit high stability, accuracy, and long-term usability (Xu et al. 2023).

The integration of pH sensors into textile substrates has emerged as a promising approach for wearable textiles. Textiles provide unique advantages; flexibility, comfort, permeability to air and water vapor, and diverse fabrication possibilities, enabling seamless incorporation of sensing elements (Saldanha & Dorval Courchesne 2025). Among various transduction mechanisms, colorimetric sensing stands out for its simplicity, non-invasive nature, and direct visual feedback. These sensors exploit pH-sensitive dyes that undergo distinct color changes with varying acidity or alkalinity, allowing rapid visual or optical readout (Boeva et al. 2024; Pour et al. 2024; Di Costanzo & Panunzi 2021).

Colorimetric textile-based sensing relies on the halochromic behavior of dyes that respond to changes in hydrogen ion concentration ([H+]) (Bamfield & Hutchings 2010; Park, Kim & Bae 2011; Feldman 1956). This property enables real-time, user-friendly monitoring in biofluids, particularly for applications such as sweat analysis and wound care. Despite these advantages, challenges such as dye leaching, limited stability, poor wash fastness, and incomplete color reversibility continue to restrict sensor reliability (Zhang, Reagan & Kaplan 2009; Van der Schueren 2008). Current research focuses on improving these limitations through optimize immobilization, encapsulation, and fabrication strategies.

The development of non-invasive, colorimetric, textile-based pH sensors represent an emerging interdisciplinary field with significant potential for personalized health monitoring. Compared to traditional wearable pH sensors that often rely on rigid substrates or bulky electronics, textile-based systems offer lightweight, flexible and more user-friendly alternatives (Heikenfeld et al. 2018). However, ensuring stability, calibration accuracy, and signal reliability, remains a crucial challenge.

Despite growing research activity, a comprehensive review addressing the recent advancements, fabrication methods and performance considerations of textile-based colorimetric pH sensors remains scarce. This review aims to fill that gap by critically evaluating advances in fabrication techniques, material design, sensor performance and practical applicability. Furthermore, it identifies key challenges and future research opportunities to guide the development of reliable and wearable pH sensing platforms for real-time health monitoring.

This review was compiled using peer-reviewed studies between 2015 and 2025. Relevant studies were identified using databases such as Scopus, Web of Science and ScienceDirect with keywords including, and the language restricted to English. The search in Google Scholar using the keywords "colorimetric textile-based pH non-invasive healthcare" yielded 710 research publications, while Web of Science using the key words “Any field contains wearable pH sensors AND Any field contains textile-based.” provided 46 research publications.

The most relevant research publications were selected based on the following criteria based on the research abstract.

- The sensor fabrication must be textile-based.
- The application must be in the health monitoring.
- The sensor must monitor pH variations non-invasively and
- The sensing method must be based on colorimetric techniques.

Considering these selection criteria, a total of 35 relevant research publications were finalized for this review.

FUNDAMENTALS OF COLORIMETRIC PH SENSORS

pH is defined as the negative logarithm of the hydrogen ion concentration (H^+) in moles per liter (Feldman 1956). It provides a standardized quantitative measure of acidity or alkalinity and can be given by the following equation:

$$pH = -log_{10} C_{H^+}$$

Where [$C_H{}^+$] represents the equilibrium molar concentration of hydrogen ion in the solution.

In biological systems, pH is tightly regulated by buffer systems present in biofluids such as blood, interstitial fluids, sweat, saliva, and tears (Chung et al. 2021; Morris et al. 2009). These fluids are easily accessible and offer non-invasive means for monitoring physiological processes as their pH reflects metabolic and systemic conditions (Diculescu et al. 2019).

The pH of human blood is precisely regulated between 7.35 and 7.45, as deviations from this range may result in acidosis or alkalosis, both of which can lead to severe health complications (Boeva et al. 2024; Choudhry et al. 2021). In comparison, the pH of sweat typically ranges from 4.5 to 7.0 and varies depending on electrolyte composition, particularly sodium (Na^+), potassium (K^+), and chloride (Cl^-) (Mao, Li & Yu 2023; Hatamie et al. 2020).

The concept of pH sensing originated in 1909 when Fritz Haber and Zygmunt Klemensiewicz introduced the first commercial pH electrode, followed by the first commercial pH meter developed by Arnold Beckman in 1930 (Marczewska & Marczewski 2010; Laffitte & Gray 2021). While, glass pH electrodes remain highly accurate, they suffer from limitations such as fragility, bulkiness, and frequent calibration requirements, making them unsuitable for continuous or wearable applications.

The development of chromic dyes led to halochromic materials, capable of changing color in response to pH variations (Bamfield & Hutchings 2010; De Meyer et al. 2016). Integrating these dyes into textiles substrates has enabled the creation of wearable colorimetric pH sensors that offer real-time, non-invasive health monitoring (Caldara et al. 2016). Colorimetric pH sensors function by protonation or deprotonation of pH-sensitive dyes, altering their electronic structure and light absorption properties (Alisaac et al. 2022). This molecules transformation produces a visible color change corresponding to specific pH values, allowing simple visual or optical quantification (Bamfield & Hutchings 2010; Park, Kim & Bae 2011)

Compared with electrochemical and fluorescence-based sensors, colorimetric sensors are simpler and more cost-effective and easier to fabricate (Promphet et al. 2019; Magnaghi et al. 2024). However, their sensitivity is typically lower and may require calibration, they eliminate the need for specialized detection systems (Seo et al. 2024). Recent advancements in textile-based colorimetric sensors have demonstrated enhanced flexibility, comfort, and integration with daily wear. Studies using cotton and silk fabrics functionalized with halochromic dyes have shown promising results for wearable applications (Tasangtong et al. 2024; Ghadge et al. 2024). These systems represent a major step toward affordable, continuous and user-friendly health monitoring platforms.

Understanding the fundamental principles of pH sensing is essential for developing advanced, non-invasive wearable devices. The shift from traditional electrochemical systems to colorimetric and textile-integrated approaches marks a significant improved in usability, affordability, and real-time diagnostic capabilities.

The performance of wearable colorimetric pH sensors is strongly influenced by the choice of substrate and the method of functionalization. These factors determine sensor sensitivity, accuracy, and reliability under dynamic physiological conditions. Textiles with their inherent flexibility and structural versatility, have emerged as an ideal substrate for developing wearable sensors due to their ability to combine comfort, permeability to air and water vapor and adaptability to body motion.

Textiles offer a wide range of structures in fibers, yarns, and fabrics, which can be tailored through spinning, texturing, weaving, knitting and non-woven process. Composites structures created by combining different fiber and polymer materials provide further versatility for sensor integration. This structural diversity makes textiles highly adaptable for functional applications, particularly as sensor substrates. The most advanced research in this field focuses on fully textile-based sensor devices, emphasizing flexibility, portability, non-invasiveness, and lightweight design for continuous body monitoring. These devices are not only user-friendly but also eco-friendly, leveraging textile manufacturing infrastructure for scalable production (Possanzini et al., 2020).

In biomedical field, textile-based sensors are exclusively utilized for monitoring physiological and biomedical parameters. Successful realization of these systems require proper attention to fabric morphology, mechanical deformation and moisture interactions, which can significantly influence sensor performance, accuracy and durability (Yang et al. 2010).

Selecting an appropriate textile substrate is critical for achieving optimal sensor performance. The substrate determines not only the mechanical properties and user comfort, but also stability and signal reproducibility of sensing mechanism (Azeem et al. 2024). In most cases, the same textile is used for the sensing element and the wearable base, enabling seamless integration into garments and improved wearability. As an example, Zhou et al. (2022) developed a textile-based wound dressing sensor that can perform chemical measurement on wound exudate. Their aim was to create a system with use of cotton fabric as a substrate for a pH-responsive sensor, where the fabric is covalently immobilized with a pH-sensitive dye, allowing for chemical sensing directly within the cotton material. This integration is crucial for unobstructive monitoring during the wound healing process (Zhou et al. 2022).

Key selection parameters include:

- Biocompatibility and comfort particularly important for long term skin contact applications (Promphet et al. 2019; Ghadge et al. 2024).
- Flexibility and stretchability to accommodate body movements without compromising the sensor functionality (Xi et al. 2023; Ha et al. 2023).
- Mechanical durability of the sensor substrate must withstand repeated mechanical stresses, such as bending, stretching, washing and rubbing (Ghadge et al. 2024; Tasangtong et al. 2024).
- The hydrophilicity and wicking ability of the sensor is crucial for effective biofluid absorption and rapid transport to the sensing zone (Caldara, Colleoni, Guido, et al. 2012; Kuswandi, Irsyad & Puspaningtyas 2023)

Among natural fibers, cotton remains the most widely used substrate for textile-based colorimetric pH sensors. Cotton offers exceptional properties such as flexibility, biocompatibility, high surface area, and comfort, making it highly suitable for wearable health monitoring. Its hydrophilic nature facilitates effective dye absorption and fluid diffusion, while the high surface area allows uniform dye deposition and diffusion, without compromising permeability to air and water vapor (Rosace et al. 2017; Snari et al. 2022). The moisture absorption properties of cotton fibers support rapid transport of sweat or other bodily fluids to the sensing area, enhancing response time and color uniformity (Zhu, 2023).

The type of fabric structure has also been reported to impact sensor performance, with several different fabrications such as plain, twill and cotton-spandex blends having been examined. In a study Salaün et al. (2023) showed that use of cotton twill has made the sensor air and water permeable, soft, and versatile, though it often requires functionalization to enhance dye affinity (Salaün 2023). Meanwhile, the cotton-elastane blend combines permeability of cotton material with stretchability of elastane, offering additional comfort and elasticity for wearable sensors (Seo et al. 2024). Studies have highlighted excellent absorption properties of cotton and its ability to produce long-lasting, vibrant colors, which make it ideal for sweat pH sensors (Zhu et al. 2023). Cotton's biodegradability, low cost and wide availability further support its adoption for sustainable wearable sensors (Petkovska et al. 2024; Promphet et al. 2019).

In addition to cotton, other natural fibers like wool and silk have also attracted attention. Wool shows high dye uptake due to its abundant amino groups and amorphous structure (Ghadge et al. 2024), while silk, offers strength, biocompatibility and luster, making it suitable for both medical and aesthetic applications (Ribeiro et al. 2023). Both materials present specific advantages, such as better dye absorption and dye stabilization than cotton, which make them enhanced dye retention and reduced leaching, improving long-term sensor stability.

However, cellulose-based fibers such as cotton have limited functional groups for strong dye bonding often necessitating surface (Petkovska et al. 2024) functionalization or the use of mordants to improve due-fiber interactions (Promphet et al. 2019). Synthetic fibers, in contrast, can be engineered with specific functional groups to improve dye bonding strength and moisture responsiveness, offering tunable alternative for performance optimization. Collectively, the inherent dye affinity, permeability to air and water vapor, and biocompatibility of cotton, wool, and silk highlight their strong potential as substrates for natural-dye-based wearable pH sensors.

The physiological interaction between dye molecules and fiber substrates plays an important role in colorimetric sensor stability and sensitivity. Meyer et al. (2016) demonstrated that the dyeing pH-sensitive polyamide 6 (PA6) fibers, at different pH solution levels alters dye-fiber affinity, influencing sensor response and dye retention (De Meyer et al. 2016). Similarly, Peila et al. (2021) compared multiple fiber types such as wool, polyacrylonitrile, polyester, polyamide 6.6, cotton, and cellulose acetate, dyed with Bromocresol Purple and Chlorophenol red, showing that fiber chemistry strongly affects dye uptake and wash fastness (Peila et al. 2021).

PH-SENSITIVE DYES AND STABILIZATION APPROACHES

PRINCIPLE AND SELECTION OF PH-SENSITIVE DYE

The colorimetric pH sensors reply on halochromic dyes; compounds that exhibit visible and reversible color changes in response to variations in hydrogen iron concentration. This behavior results from the protonation and deprotonation of the dye's functional groups, which alter its electronic structure and optical absorption properties (Petkovska et al. 2024). Each dye has a characteristics pKa, defining the pH at which it transitions between protonated and deprotonated states (Alisaac et al. 2022). In textile-based pH sensors, the selection of suitable dyes depends on several key factors: i) pH sensitivity range relevant to the biological target (typically pH 4-8 for sweat or wound analysis), ii) color contrast and reversibility, iii) photochemical and thermal stability, iv) affinity for the textile substrate, and v) safety for prolonged skin contact. Reversible color change is essential for continuous use and ensures reproducibility and longevity (Snari et al. 2022).

NATURAL HALOCHROMIC DYES

Driven by sustainability and biocompatibility research has increasingly focused more on natural dyes such as anthocyanin, curcumin, and betalains, driven from plants, fruits and vegetables (Salaün 2023; Yang et al. 2024). These natural dyes biodegradable and often exhibit additional antibacterial, antimicrobial, and antioxidant properties, which enhance their suitability for medical and wound-healing applications (Ghazal & Elshamy 2024; Yin et al. 2017; Alehosseini et al. 2019). Anthocyanins are among widely studied natural halochromic dyes. They exhibit multi-color transitions from red to purple to blue to green, depending on pH due to structural transformations between flavylium cations and quinoidal bases.

Plants generally derive their color from organic chemicals or phytochemicals such as azo compounds, anthocyanins, flavones, xanthine, and flavonols (Rao & Seshadri 1943). These pigments exhibit pH-dependent variations in their color spectra (Lowry & Chew 1974; Roy & Rhim 2021; Sigurdson & Giusti 2014). Among them, anthocyanins are natural halochromic flavonoid dyes characterized by a C_6-C_3-C_6 carbon network and occur as glycosides of flavylium cations. Proton exchange involving hydroxyl and methoxy groups is regarded as the primary mechanism driving their pH-responsive color transitions (Houghton, Appelhagen & Martin 2021).

Previous studies have employed anthocyanin rich extracts from various botanical sources, such as red cabbage, black rice, purple sweet potatoes, grape, blueberry, black bean, black carrot and mulberry to dye natural textile materials including cotton, silk, and wool fibers (Haddar et al. 2018; Punyachareonnon, Deerattrakul & Luepong 2021; Koh & Hong 2017; Pars & Karadag 2024). The stability of these dyes is strongly influenced by various environmental and chemical factors, including pH, temperature, light exposure, oxygen, chemical composition, solvent, co-pigments, metal ions, and enzymes (Câmara et al. 2022; Sigurdson & Giusti 2014; Wang, Tang & Zhou 2016; Bandodkar, Jeerapan & Wang 2016). Beyond their coloring ability, anthocyanins have shown notable functional properties, such as antioxidant, anti-inflammatory, anticancer, and antimicrobial properties while serving as a natural halochromic dye (Cui et al. 2020; Alaysuy et al. 2022; Gupta, Chahal & Bhatia 2015; Karastathi, Salmane & Parker 2024). Alaysuy et al. (2022) further highlighting the pH-sensitivity of anthocyanins extracted from red cabbage by demonstrating marked color transition: red in highly acidic media, pink under weakly acidic conditions, green in mildly basic environment, and colorless in strongly alkaline solutions.

Mordants such as alum play a critical role in improving the fixation, stability, and durability of natural dyes on textile fibers. Alisaac (2022) employed alum as a mordant to immobilize anthocyanin dyes on cotton fabrics, with SEM analyses confirming the formation of alum-anthocyanin deposits on the fiber surface. Their results highlighted the inherent low stability of natural dyes and the necessity of mordants to improve dye fixation. In contrast, Tasangtong et al. (2024) reported that anthocyanins extracted from butterfly pea flowers exhibit distinct halochromic transitions, red-to-purple shift at pH 1–5, a blue-to-green transition at pH 6–12, and light-green appearance above pH 12, highlighting their versatile halochromic behavior. These color variations among anthocyanin sources result from differences in their molecular structures, which govern pH-dependent protonation and deprotonation equilibria and consequently alter their absorption characteristics (Alisaac et al. 2022; Petkovska et al. 2024). Unlike many conventional pH indicators, anthocyanin-based dyes display a unique ability to exhibit multiple color changes in response to a wide range of pH levels. Cellulose nanofibers modified with red cabbage anthocyanin extract resulted in reversible and universal pH sensing capabilities across a wide pH range (Devarayan & Kim 2015).

Despite their advantages, natural dyes can exhibit several limitations, including variable stability, inconsistent color fastness, and restricted pH-responsive behavior. Natural dyes are also highly susceptible to environmental factors such as heat, temperature, humidity, light, and pH, which can accelerate degradation and reduce functional stability over time (De Meyer et al. 2016). Furthermore, their extraction and purification often require more time and incur higher costs compared to the synthetic alternatives.

Curcumin has been widely investigated for colorimetric sensing due to its pH sensitivity (Ha et al. 2023; Yang et al. 2024). Chemically, curcumin (1,7-bis(4-hydroxy-3-methoxyphenyl)-1,6-heptadiene-3,5-dione) is a low-molecular weight hydrophobic polyphenolic compound of turmeric (Curcuma longa L.) (Salaün 2023; Pourreza & Golmohammadi 2015). Its color changes arise from protonation and deprotonation mechanisms that alter electronic configuration. This results changes in interaction with visible light with the transitions governed by its acidity constant (Peila et al. 2021). Curcumin also undergoes keto-enol tautomerism; in acidic to neutral media (pH 3–7), the dominance of the keto form produces a yellow solution, whereas in alkaline conditions the enol form leads to a red chromatic shift (Pourreza & Golmohammadi 2015; El-Sedik et al. 2024; Peila et al. 2021; Chung et al. 2021). Beyond its halochromic behavior, curcumin is well known for bearing the properties of antioxidant, anti-fungal, anti-inflammatory, anticarcinogenic, antibacterial, and wound healing (El-Sedik et al. 2024; Pourreza & Golmohammadi 2015). A notable limitation of curcumin exhibits it's restricted color transitions and hence does not cover the broader pH spectrum required for certain applications (Ribeiro et al. 2023).

Ha et al. (2023) developed a wearable colorimetric sweat pH sensor using curcumin-dyed thermoplastic polyurethane nanofibers, providing rapid and visually intuitive color transitions suitable for continuous monitoring, particularly in cystic fibrosis patients. However, challenges such as reduced stability under extreme pH and limited long-term durability must be addressed before these sensors can be translated into practical, real-world applications.

In summary, natural dyes provide biocompatibility and sustainability advantages compared to synthetic dyes but with limitations such as restricted pH range, lower stability and environmental sensitivity, which require further research and innovation to overcome.

SYNTHETIC HALOCHROMIC DYES

Synthetic dyes, including azo, sulfonphthalein and hydrazone-based indicators, offer enhanced stability, sharp transition ranges and tunable structures. Their commercial availability and consistent performance make them a popular choice for quantitative sensing applications (Magnaghi et al. 2024; Ribeiro et al. 2023). Synthetic pH indicators have shown better stability than natural dyes owing to their high resistivity towards environmental factors such as light, temperature and humidity (Wang et al. 2025). The bulk production has made synthetic dyes more accessible and less expensive.

TRICYANOFURAN-HYDEAZONE

Snari et al. (2022) and Abdelrahman et al. (2020) employed tricyanofuran-hydrazone as a halochromic chromophore in wearable colorimetric pH sensors for the detection of bacterial pathogens, demonstrating its potential for various applications, including sweat pH monitoring. Their findings demonstrate that tricyanofuran-hydrazone acts as an efficient halochromic and biochromic indicator, producing a broad spectrum of colors in response to pH variations. This behavior is attributed to the reversible protonation and deprotonation of the tricyanofuran-hydrazone chromophore (Snari et al. 2022; Abdelrahman et al. 2020). Specifically, the chromophore exhibits yellow to orange hues under acidic conditions, red to wine-red in neutral media, and violet to purple in alkaline environments. Snari et al. (2022) further demonstrated that the growth of E. coli (Gram-negative bacteria) released ammonia and volatile amines as metabolic byproducts, increasing the local pH and inducing a colorimetric shift from red to green. Conversely, the growth of L. acidophilus generated lactic acid, lowering the pH and producing a colorimetric change from red to yellow.

SULFONPHTHALEIN DYES

Many sulfonphthalein dyes such as phenol red, bromocresol green, bromothymol blue, chlorophenol red and bromocresol purple are commonly used due to their clear color changes and compatibility with a wide range of textile substrates (Jankowska et al. 2017). Sulfonphthaleine dyes are widely used as acid-base indicators due to their distinct halochromic transitions across acidic to alkaline environments (De Meyer et al. 2016). At low pH, these dyes predominantly exist in their neutral form; with increasing pH, stepwise deprotonation produces monoanionic and subsequently dianionic species, each associated with a characteristic color change. A range of sulfonaphthalein derivatives including phenol red (Promphet et al. 2020), bromocresol green (Promphet et al. 2019; Zhou et al. 2024), bromothymol blue, chlorophenol red (Kuswandi, Andriani & Nugraha 2022), and bromocresol purple (Peila et al. 2021), have been adapted for wearable colorimetric pH sensors. Structural tuning of these dyes commonly involves substituting hydrogen atoms on the xanthene or phthalein core with electron-donating groups (e.g., $–CH_3$) or electron-withdrawing halogens (e.g., Br, Cl), which modulate halochromic behavior and dye–textile interactions (De Meyer et al. 2014). Meyer et al. (2016) have shown the important role of substituents for the development of halochromic dyes and their possible interactions with the textile materials. Kuswandi et al. (2023) integrated a novel wearable colorimetric sensor into a pain relief patch for non-invasive simultaneous analysis of sweat lactic acid, sodium ions, and pH during physical activities. The use of chlorophenol red as a synthetic pH indicator allows for effective monitoring within a specific pH range, with color changes indicating varying acidity. Chlorophenol red (CPR) was selected as a pH indicator because it has a pH range between 4.6 and 7.0 (aligning with the normal pH range of sweat) and a color change from yellow to red in response to varying pH levels was observed (Kuswandi, Irsyad & Puspaningtyas 2023). Their findings reveal that different CPR concentrations give different intensities of color change with pH changing from 4 to 7.

AZO DYES

pH-sensitive Azo dyes have also been explored for textile-based colorimetric pH sensing. Ribeiro et al. (2023) developed a halochromic silk fabric functionalized with the synthetic azo dye to create a flexible and biocompatible pH sensor capable of visibly indicating pH variations (Ribeiro et al. 2023). They stated that this was a special type of Azo dye with hypochromic shift from blue (561 nm) to magenta (541 nm) and color variation in the dye in pH ranging from 3 to 12, the color of silk samples dyed at pH 6 dipped in different buffer solutions. The visible color change was even detected at lower concentrations, such as from 8 to 32 $\mu g \cdot mL^{-1}$ of the dye in the fabric, and high dye stability was noticed at higher pH since no dye leaching was observed in UV-Vis spectroscopic analysis. This halochromic dye is ideal for disposable and non-washable applications due to poor resistance to washing (Ribeiro et al. 2023).

Multiple pH indicators have also been combined to broaden sensing ranges in textile-based systems (Kuswandi, Andriani & Nugraha 2022; Promphet et al. 2019; Agarwal et al. 2012). Mei et al. (2023) integrated a universal pH indicator solution into nanofibers for detecting pH levels through observable color changes. Zhou et al. (2024) introduced an innovative textile-based colorimetric sensor utilizing synthetic dyes methyl orange (MO) and Bromocresol Green (BCG) with a combined pH sensitivity range of 3.1 to 10 for monitoring sweat pH. MO and BCG exhibited color transitions in the pH ranges of 3.1–4.4 and 3.8–5.4, respectively, causing compound indicators to shift from yellow to green with the increase of pH value. This combination allows for a broader detection range and improved color contrast, which is essential for accurate pH measurement in sweat (Zhou et al. 2024).

FABRICATION

The evolution and advancement in dye immobilization for pH sensor fabrication and development have been marked by the integration of natural dyes and innovative immobilization techniques, aimed at enhancing performance, stability, and applicability, particularly in wearable technology and biomedical applications. The evolution of dye immobilization techniques, whether via physical entrapment or chemical bonding, has paved the way for the integration of pH sensors into wearable technology. The key methods are dyeing, electrospinning and surface modification with various coatings such as sol-gel, cross-linking, encapsulation, nanocomposites, chemical bonding, and polymerization.

DYEING AND PRINTING

Dyeing has been widely used in developing textile-based pH sensors. In the dyeing process, standard water-soluble pH-sensitive dyes are used as colorants in the conventional textile dyeing process (van der Schueren & de Clerck 2011). This method is straightforward and easy but often results in poor dye stability and subsequent leaching, which limits the practical use of the as-fabricated sensor in prolonged periods. De Mayer et al. (2016) showed that sulfonphthalein dyes on polyamide fabrics via dyeing led to a high leaching rate in aqueous solutions, consequently with reduced effectiveness of the pH sensor. The dye-fiber interactions are considered as the driving force in the dyeing process to determine the durability of the as-developed sensors. The conventional dyeing process can generate vibrant colors with a wide range of dye options; however, dye leaching and reduced wash fastness are critical issues that compromise the stability and sensitivity of the pH sensor. In another case, phenolphthalein, a well-known pH indicator with color-changing capability from colorless to violet in base solutions, was effectively immobilized onto traditional textiles (i.e., cotton and nylon) via dyeing (Zhang et al. 2009; Van der Schueren 2008; Van Der Schueren et al. 2010). Curing processes are usually conducted to enhance the dye fixation with dye molecules well-anchored to the fabric, resulting in reduced dye leaching and enhanced durability of the colorimetric response (Peila et al. 2021).

Screen printing methods allow precise deposition of materials onto textile substrates, ensuring channel separation between different detection zones (Promphet et al. 2019; Alisaac et al. 2022). The screen-printed layers can enhance the specificity of the sensor by creating distinct areas for pH and lactate detection, which is crucial for accurate measurements. Tasangtong et al. (2024) used the stencil transparent film-printing method to fabricate pH sensors, resulting in patterned cloth-based sensors. The stencil printing method provides high-resolution structures for hydrophilic channels and hydrophobic barriers, enabling effective sweat analysis in resource-limited settings. Plasma treatment was employed to modify the surface properties of textile substrates with enhanced dye adhesion in developing pH sensors (Peila et al. 2021). Plasma treatment significantly reduced dye leaching and improved the overall responsiveness of the textile to pH variation. Both conventional dyeing techniques and advanced dye immobilization methods can synergistically anchor pH-sensitive dyes onto the textile materials. Various dye immobilization methods have been employed in this regard, such as physical adsorption, covalent bonding (Zhou et al. 2022), encapsulation (Peila et al. 2021), mordanting (Ghadge et al. 2024), electrospinning with dye functionalized solutions (Mei et al. 2023), physical adsorption, layer-by-layer (LbL) assembly (Petkovska et al. 2024), and conventional dyeing techniques (De Meyer et al. 2016).

ELECTROSPINNING

Electrospinning has been utilized to create nanofiber-based sensors with pH-sensitive dyes. Mei et al. (2023) developed a nanofibrous film for simultaneous detection of multiple biomarkers including pH. They showed that electrospinning has promoted uniform dye distribution within the fibrous matrix. Their findings revealed that electrospun nanofibers provided a large surface area for the interaction with analytes, thus improving the sensor sensitivity. For electrospinning, the polymer and dye molecules are dissolved in suitable solvents as the electrospinning solution, and the dye molecules are entrapped in the fibers after evaporation of solvents (Schoolaert, Hoogenboom & De Clerck 2017). Dye-doping, i.e., adding dyes to the polymer solution prior to electrospinning, is the most accepted method of coloring nanofibrous materials (Schoolaert, Hoogenboom & De Clerck 2017). Apart from the fact that electrospinning is simple, scalable, and reproducible, nanofibers can enhance the sensitivity of sensors due to their large surface area and the ability to create enhanced number of sites for analyte detection, thus improving the sensor sensitivity and the fast response (Chung et al. 2021). Dye-doping method was also used to immobilize sulfonphthaleine dyes onto PA6 nanofibers, but significantly higher dye leaching compared to conventional dyeing methods was noticed (De Meyer et al. 2016). This increased leaching was due to the highly acidic electrospinning solution. During electrospinning, the dyes in their neutral or anionic form led to weaker interactions with the PA6 matrix. Consequently, at aqueous solutions, the dyes exhibited poor retention, as the conditions favored their solubility and migration out of the textile material. The pH value of the polymer solution and the fiber diameter were found to influence dye leaching and pH sensor sensitivity, i.e., the pH of the polymer solution determining the state of the dye molecules (neutral, protonated, or deprotonated) while the fiber diameter affects the interaction between the dye and the fiber.

SURFACE MODIFICATIONS

Chemical bonding has been heavily used to improve the stability and performance of pH sensors. Chemical crosslinking or bonding methods chemically attach halochromic dyes or pH indicators to the textile surface using functional groups such as amine, hydroxyl, or carboxyl. The use of covalent bonding methods has emerged as a robust strategy for dye immobilization, offering permanent dye fixation with minimal dye leaching. This dye immobilization method ensures highly durable, washable and reusable colorimetric pH sensors. Cui et al. (2020) used chitosan, specifically hydroxypropyl trimethyl ammonium chloride chitosan (HACC), to modify calcium alginate fibers for enhanced dyeing uptake as the charge repulsion between the negatively charged dyes (anthocyanin and alizarin) and the fiber was reduced, thereby facilitating better dye uptake. They also noticed that the modification with HACC provided antibacterial properties to the fibers, making them suitable for medical applications such as wound dressings.

Jia et al. (2023) revealed that physical and chemical interactions were established between the MDPD-PU microparticles composed of a waterborne polyurethane (PU) shell incorporating a self-synthesized chromophore, MDPD and the polyester fibers during the dyeing process (Jia et al. 2023). The forces that contributed to this attraction included van der Waals forces, hydrogen bonding, and electrostatic interactions, all of which facilitated durable bonding between the microparticles and the fibers, hence improving the dyeing performance and color fastness of the fabric. Zhou et al. (2024) described that chitosan enhanced the pH sensor sensitivity by facilitating the bond between the positively charged amino groups in chitosan and the negatively charged groups in the dye molecules. Chemical bonding of dye molecules to the sensor substrate also hinders the dye leaching and bleeding during the washing processes. Trovato et al. (2021) have developed a wearable sweat pH sensor by covalently immobilizing the synthetic an azo dye, e.g., Nitrazine Yellow (NY), onto a cotton fabric through a thermal-induced radical polymerization method. They explained that NY was covalently bonded on to the cotton fabric using glycidyl methacrylate (GMA) through a two-step epoxy ring-opening reaction using a catalyst, efficiently, reducing dye leaching. NMR and FTIR spectroscopic analysis were also employed to confirm the covalent immobilization, validating the chemical interactions and durability of the pH sensitivity of the fabric. In another study, covalent bonding was used in the development of a wearable flexible sweat pH sensor based on SERS-active Au/TPU electrospun nanofibers, with good stability and no statistically significant decline in performance after 35 days (Chung et al. 2021). Promphet et al. (2019) found that the introduction of cetyltrimethylammonium bromide (CTAB), a chemical crosslinking agent, has improved the durability of methyl orange and bromocresol blue dyes within the sensor structure. The crosslinked structure provided a stable environment for the dyes, ensuring the consistent performance over the time (Promphet et al. 2019). Zhou et al. (2022) fabricated a stable, reusable, and rapid response pH-responsive textile sensor by covalently immobilizing a naphthalimide-rhodamine probe onto cotton fabrics. Their findings revealed that covalent bonding ensured strong adhesion of the dye to the substrate while enhancing the durability and washability of the sensor.

The sol-gel method has been developed as another effective tool for dye immobilization. Caldara et al. (2016) developed a pH-sensor for healthcare pH analysis using a cotton fabric treated with an organically modified silicate (ORMOSIL) together with miniaturized and low-power electronics with wireless interface. This approach used organically modified silicates (ORMOSIL) to create a stable matrix for pH-sensitive litmus dye. The pH-sensitive ORMOSIL was developed via the sol-gel method by using 3-glycidoxypropyltrimethoxysilane (GPTMS) as siloxane precursor. According to Rosace et al. (2017), the pH sensor developed by combining GPTMS (3-glycidoxypropyltrimethoxysilane) and resorufin resulted in effective dye immobilization within the silica network, preventing dye leaching while maintaining enhanced pH sensitivity. The sol-gel method also facilitated a durable coating on the textile material, which can withstand washing and resist degradation from environmental exposure.

Hydrogels were also used to trap and immobilize dyes in their matrix. This method is emerging as a powerful tool for the colorimetric pH sensor development. Hydrogels can encapsulate pH-sensitive dyes like anthocyanins by providing a responsive medium that can swell or shrink based on pH changes. Tasangtong et al. (2024) have developed a biocompatible and biodegradable textile-based sweat sensors by immobilizing natural dyes (extracted from butterfly pea flower, turmeric, and red cabbage) using a hydrogel, sodium carboxymethyl cellulose (NaCMC). Enhanced dye stability was noticed with enhanced sensor stability and performance as the dye molecules were held in place, and dye leakage during pH analysis was largely prevented. The hydrogel approach was also found to enhance the sensitivity and response time of the sensor (Karastathi, Salmane & Parker 2024).

Encapsulation, such as microencapsulation, allows for the integration of pH-sensitive dyes within a polymer matrix. This method not only protects the dye but also facilitates its interaction with the surrounding environment, leading to rapid and reversible color changes in response to pH fluctuations. Abdelrahman et al. (2020) developed a colorimetric pH sensor for real-time monitoring of sweat pH by encapsulating a synthetic tricyanofuran-hydrazone dye in calcium alginate microcapsules followed by immobilization on cotton fabrics. The encapsulation protected the dye from environmental factors but also allowed for controlled release and interaction with the analyte, leading to excellent responsiveness of the sensor. Salaün et al. (2023) also used microcapsules to encapsulate curcumin in semi-porous membranes to create a more stable and responsive pH sensor. They emphasized that this method enhanced the durability of the dye in the textile matrix and realized controlled release by improving the reliability of the sensor (Salaün 2023).

Multilayered coating further advanced dye immobilization by creating complex sensing environments that enhanced the sensitivity and selectivity of pH sensors. Promphet et al. (2019) used layers of chitosan and sodium carboxymethyl cellulose (NaCMC) as a matrix to support the pH indicators, demonstrating better interaction with sweat and other biological fluids. Petkovska et al. (2024) further developed an environmentally friendly real-time pH monitoring wound dressing by immobilizing anthocyanin grape dye on cotton fabric via Layer-by-Layer assembly of biopolymers including chitosan and pectin. These coatings immobilized dyes effectively while providing additional benefits such as biocompatibility and antimicrobial properties.

Electrostatic assembly techniques, which utilize the charge properties of both the dye and the substrate to facilitate immobilization, were used to develop a more uniform coating of pH-sensitive dyes on various substrates, including threads and fabrics. For example, curli fibers, which are genetically engineered proteins, have been successfully coated onto threads using electrostatic interactions, providing a robust and responsive pH sensing platform (Saldanha & Dorval Courchesne 2025).

The performance of colorimetric pH sensors after prolonged exposure to biofluid, humidity, mechanical stress, and strain may undergo significant changes as a result of dye leaching, altering moisture-dye interactions, and altering the structural integrity of the dye molecules in the sensor (Seo 2024, Promphet 2019, Mei 2021, Caldara 2012). The continuous contact with biofluids, like sweat, may cause leaching of the pH indicator dye, resulting in reduced sensitivity and accuracy (Ghadge et al. 2024). High humidity levels result in increased moisture content surrounding the sensor, leading to alterations in the dye and moisture interaction and thus inaccurate colorimetric reading (Seo et al. 2024). The repeated mechanical strains, such as bending and stretching of the sensor material, may lead to inconsistency in the sensor response due to physical damage to the sensor structure, hence weakening the integrity of dye-textile materials (Mei et al. 2023; Caldara, Colleoni, Galizzi, et al. 2012). The dye immobilization and integrity within the primary textile materials will be disturbed under these stresses and strains, causing a loss of color stability and reproducibility. Tasangtong et al. (2024) have developed a patented textile-based wearable sensor capable of detecting sweat biomarkers, including pH, lactate, and chloride. In this work, a novel stencil transparent film-printing was employed to immobilize several natural indicators, including butterfly pea flower extract, curcumin, and purple cabbage extract, on cotton fabrics pre-coated with chitosan and sodium carboxymethyl cellulose (NaCMC). The hydrogel layer formed by NaCMC effectively entrapped the natural indicators, hence enhancing dye stability and reducing dye leaching during application. The authors noted that this immobilization resulted in higher color intensity and enhanced long-term stability of the indicators in comparison to the non-NaCMC immobilization. Petkovska et al. (2024) developed a pH-indicating cotton fabric wound dressing by using biocompatible materials, i.e., chitosan, and pectin, combining with anthocyanin dye extracted from grapes. They used layer-by-layer assembly for the dye immobilization, allowing precise multiple layer depositions of chitosan and pectin along with the anthocyanin dye onto the cotton fabrics. This multilayer structure created a flexible, robust coating, hence reducing the dye leaching in biofluids and acting as a barrier for humidity and mechanical stress. The flexibility of the sensor improved the stability of the sensor during mechanical deformations without compromising the dye stability. Abdelrahaman et al. (2020) designed a textile-based sweat pH sensor via immobilizing encapsulated tricyanofuran-hydrazone within calcium alginate microcapsules followed by pad-dry-cure coating onto cotton fabrics. The microencapsulation of the dye with calcium alginate has significantly improved sensor performance, stability, responsiveness, accuracy, usability, reversibility, and real-world application by protecting the dye from degradation due to light and moisture, controlling dye release, reducing premature dye leaching, providing increased surface area, adding more sites for dye-analyte reaction, and allowing dye to undergo reversible protonation and deprotonation processes.

In summary, the evolution of dye immobilization techniques in pH sensor fabrication has transitioned from traditional dye application with significant limitations to advanced techniques such as electrospinning, sol-gel processes, hydrogel systems, encapsulation, chemical crosslinking, advanced coating. The advancements in dye immobilization for pH sensor fabrication have transitioned from simple physical methods to sophisticated chemical and electrostatic techniques. These advancements have led to the significant improvement in stability, sensitivity and development of more reliable, durable, and effective pH sensors suitable for various applications, particularly in wearable technology and healthcare settings.

SENSOR DESIGN AND INTEGRATION

The design and fabrication method of pH sensors focus on enhancing performance and wearability over prolonged use. In recent years, sensor development has emphasized miniaturization, multi-analyte detection, dual sensing modes (colorimetric and electrochemical), integration of microfluidic systems for controlled and continuous monitoring, user-centered design, digital output integration, and cost-effective fabrication methods. These strategies collectively contribute to the development of effective, durable, and user-friendly sensors for applications in health monitoring and environmental sensing.

Advances in fiber technology have enabled the development of miniaturized pH sensors that can be integrated into wearable devices. In this regard, nanofibers and nanocomposites are widely used for pH sensor development. Nanofibers can be functionalized with pH-sensitive dyes and indicators, resulting in a high surface area for sensing and rapid response times. Promphet et al. (2020) developed a simultaneous sweat glucose and urea (via pH) sensor with cotton fibers covered with cellulose nanofibers. The sensor measured urea by immobilizing urease enzyme on the modified cotton fibers. Phenol red, a pH indicator, was employed to detect the pH changes resulted from the enzyme after catalyzing the hydrolysis of urea. It was found that the presence of a larger surface area for immobilization of the pH-sensitive dye enhanced the interaction between the dye and the sweat analytes, hence resulting in improved detection capabilities and more pronounced color changes in response to pH variations.

In another study, Mei et al. (2023) fabricated a wearable microfluidic system by integrating electrochemical and colorimetric sensing arrays. The universal pH indicator was immobilized in polyethylene oxide (PEO) and polyvinyl alcohol (PVA) nanofibers for real-time monitoring of glucose, lactate, pH, and Cl metabolites. They emphasized that the improvements in the sensor properties, such as improved analyte interaction, conformal contact with the skin, and secure immobilization of dye, were due to the high surface area and flexibility of the nanofibers. Chung et al. (2021) developed a sweat pH sensor by immobilizing 4-mercaptobenzoic acid (4-MBA), 4-mercaptopyridine (4-MPy) and pH-indicative dyes in gold (Au)/thermoplastic polyurethane nanofibers. The results revealed that nanofibers enhanced pH sensor sensitivity, stability, and response time through increased surface area and flexibility. Yao et al. (2025) used electro-blown spinning technology to produce a patterned nanofiber membrane with anti-symmetrical wettability. They demonstrated the effective imparting patterned nanofiber membrane with directed water transport and long-term air permeability, even when saturated with water during heavy sweat.

The combination of colorimetric and electrochemical sensing methods has emerged as a powerful approach for pH detection. Colorimetric sensors utilize pH-sensitive dyes that change color in response to pH variations while electrochemical sensors measure the potential difference generated by pH changes. Recent advancements have included the development of dual-mode sensors with enhanced functionality that can detect both pH and glucose levels simultaneously, providing a comprehensive health monitoring solution (Promphet et al. 2020; Mei et al. 2023).

Recent research has focused on developing textile-based colorimetric sensors that can detect multiple biomarkers simultaneously, providing valuable information about an individual's metabolic state (Promphet et al. 2019). Promphet et al. (2019) proposed a non-invasive textile-based colorimetric sensor for the simultaneous detection of sweat pH and lactate, where cotton fabric was used as the substrate material for both the sensing unit and the wearable component. In that work, three layers were deposited onto the cotton fabric chitosan, sodium carboxymethyl cellulose, and then either an indicator dye or a lactate assay and monitoring of color shifts allowed estimation of both pH and lactate concentration. Mei et al. (2023) achieved simultaneous measurements of multiple analytes by creating a nanofiber-based microfluidic system with integrated electrochemical and colorimetric sensing arrays for multiplex sweat analysis. Their findings revealed that the layered architecture enabled independent operation of individual sensing units, minimized cross-contamination, and enhanced the accuracy of simultaneous measurements. Direct ink writing, which precisely deposits sensing materials into predefined microfluidic structures, further supported the integration of multimodal sensors while maintaining device flexibility and miniaturization (Mei et al. 2023).

Hydrophilic components like cotton and silk are also integral to textile based microfluidic systems that enable directed biofluid transport. Zhao et al. (2022) utilized mercerized cotton threads in combination with hydrophobic fabric to achieve controlled sweat collection, highlighting the importance of substrate selection for precise sample handling in wearable devices (Zhao et al. 2021; Xiao, He, Qiao, Wang, et al. 2020). Oher natural polymers such as calcium alginate fiber also exhibit hygroscopic and biocompatible properties for medical applications such as wound dressings (Cui et al. 2020)

The incorporation of microfluidic systems into pH sensors has revolutionized sensor design by enabling precise fluid control and sample handling. Microfluidic systems developed with hydrophilic fibers, yarns, fabrics and nanofibrous materials have been integrated into pH sensors to facilitate the efficient collection and analysis of small volumes of biological fluids (Yu et al. 2023; Promphet et al. 2020; Kuswandi, Andriani & Nugraha 2022). This capability is particularly useful in medical diagnostics, where accurate measurements of sweat or other bodily fluids are critical (Promphet et al. 2020). Wearable microfluidic devices, as described by Xiao et al. (2020), allow for the capture and analysis of sweat, enabling non-invasive monitoring of sweat pH levels. In their study, thread-based microfluidic channels were employed to direct sweat toward sensing chambers, facilitating real-time analysis of pH and lactate biomarkers. This integration allows for the simultaneous measurement of pH and other analytes such as glucose and lactate, which has enhanced the diagnostic capabilities of wearable devices. For example, Wang et al. (2025) combined microfluidic platforms with flexible electronics to produce a compact, multifunctional wearable sensor capable of continuous physiological monitoring.

The integration of AI technology represents a significant advancement in the usability of colorimetric sensors in medical applications. By analyzing colorimetric data and other sensor outputs, machine learning models can predict pH levels with high accuracy, facilitating automated analysis and reducing the need for manual interpretation (Wang et al. 2025). The integration of pH sensors with digital technologies, such as smartphones, has enhanced user accessibility and data management. Recent advancements have included the integration of digital image processing techniques, allowing for more accurate and quantitative analysis of color changes in pH sensors. This approach enables real-time monitoring through smartphone-based platforms, improving both accessibility and user convenience (Salaün 2023).

Xi et al. (2023) employed interfacial modification techniques to create a Janus fabric with opposite wettability (hydrophobic and hydrophilic sides) (Xi et al. 2023). Yao et al. (2025) developed a colorimetric sweat pH sensor by incorporating blueberry anthocyanins (ATC) into a polyvinyl alcohol (PVA) nanofibrous membrane, and the sensor demonstrated color change from red to blue in response to varying pH levels, enabling the monitoring of acid-base balance. Hydrophobicity was introduced by electro-blown spinning a layer of polylactic acid (PLA) nanofibers on top of the PVA/ATC layer. This has enhanced the moisture management capabilities and ensured long-term air permeability of the sensor, which is crucial for maintaining comfort during perspiration.

Hydrophobic treatment was also employed to modify fiber surface to prevent the leakage of pH indicator dyes. These treatments enhance the stability and reversibility of the color change in response to pH variations, thus improving the sensor's reliability. Hong et al. (2021) developed a hollow polyurethane fiber by injecting a polyurethane (PU) and tin oxide (SnO_2) composite solution into a coagulation bath which facilitated the phase separation to create a porous structure. Then, the outer and inner layer rendered hydrophobicity by treating them with a solution of (1H,1H,2H,2H-heptadecafluorodec-1-yl) phosphonic acid (HDF-PA). Finally, pH indicator solutions, including bromothymol blue (BTB), thymol blue (TB) and methyl yellow (MY), were injected into the pores of the hydrophobic hollow fibers. The fibers were then dried to solidify the dyes within the fiber structure, thereby preventing dye diffusion during exposure to acidic or alkaline environments.

The purpose of this modification was to facilitate unidirectional sweat sampling while preventing contamination of the skin from colorimetric reagents. This integrated strategy combined sweat collection with colorimetric sensing in a single textile platform, eliminating reagent backflow to the skin and improving user comfort and safety.

APPLICATIONS IN HEALTH MONITORING

Sweat presents as a useful biofluid that can be collected noninvasively and contains many useful biomarkers (Laffitte & Gray 2021). The pH level of sweat serves as an indicator of metabolic activity and the acid-base equilibrium of the body. Precise measurement of sweat pH is crucial for the early identification of several health conditions, including kidney, lung and skin diseases (Manjakkal, Dervin & Dahiya 2020). Sweat glands under the skin serve as the excretory route for drugs and metabolism. Hence, sweat serves as a valuable biomarkers reflecting the physiological condition of the body at the molecular level (Wang et al. 2020; Boeva et al. 2024). The metabolite and electrolytes presence in the sweat can influence the pH variations from its normal range, i.e., 4.5 to 7 (Boeva et al. 2024; Diculescu et al. 2019). Hence sweat pH serves as a diagnostic indicator for conditions like cystic fibrosis, alkalosis, skin diseases, and dehydration, as an example, with cystic fibrosis patients exhibiting alkaline sweat, pH up to 9 due to impaired bicarbonate reabsorption (Guinovart et al. 2014). Sweat can be collected passively or via electrochemical stimulation, making it a non-invasive biofluid for continuous health monitoring (Azeem et al. 2024; Boeva et al. 2024). Additionally, skin pH, closely linked to sweat pH, plays a key role in wound healing, dermatitis detection, and infection monitoring (Promphet et al. 2021; Azeem et al. 2024). Peila et al. (2021) revealed that textile-based pH sensors which have been created using halochromic dyes allowed for real-time monitoring of sweat pH, in particular sports and health monitoring (Peila et al. 2021).

Normal skin has a slightly acidic pH (pH of 4-6), whereas wound areas tend to be more alkaline (pH of 7.4 or higher) due to enzymatic activity and bacterial presence (Seo et al. 2024). The wound healing process is marked by dynamic pH changes that correspond to different healing stages (Wang et al. 2020). Monitoring pH in wound site can provide real-time insights into healing progress and infection status (Seo et al. 2024; Alaysuy et al. 2022; Mao, Li & Yu 2023; Guinovart et al. 2014). The routine pH monitoring can aid in wound therapy, as changes in pH can indicate infection in the wound (Yang et al. 2010). It is noted that an increased pH value in wounds is often associated with bacterial colonization and can signal potential infections (Mao, Li & Yu 2023). Ghadge et al. (2024) highlighted that altered wound pH ranging from 7 to 8.5 signaled infected wounds, which informed the body's response to treatment. Since these changes happen over time, continuous monitoring is important (Yang, Chawang & Chiao 2019). Real-time monitoring of wound pH is critical since without real-time correlation to other physiological parameters, it is difficult to provide the real condition of the wound to the medical provider. Kurecic et al. (2018) developed a colorimetric pH sensor based wound pain relief dressing by incorporating the pH-sensitive dye bromocresol green (BCG) and local anesthetic benzocaine (BZC) into cellulose acetate-based electrospun nanofibers, allowing for real-time monitoring of pH changes in the wound areas. Their findings showed that at acidic pH levels, the material appeared to be yellow, indicating a healthy healing process, while at alkaline pH levels (which might suggest infection) the color shifted to blue, providing immediate feedback on the wound's status. BZC remained in its neutral form when the pH was lower around 3.7, making it less soluble, while at higher pH (around 9.0) it dissociated and became more soluble, leading to a significantly increased release rate, crucial for pain management in infected wounds.

Colorimetric textile-based pH sensors already demonstrate promising applicants in sweat monitoring, wound dressing and skin health diagnostics. Sweat pH reflects metabolic and electrolyte balance and can indicate dehydration, cystic fibrosis or stress related changes. sensors integrated into garments or wristbands allow continuous tracking of these parameters during exercise or rehabilitation. In wound caring localized pH monitoring provides insights into healing progression and infection rick. For example, Petkovska et al (2024) and Seo et al (2024) reported textile dressings capable of changing color as the wound environment shifts from acidic (healing) to alkaline (infected) allowing early medical intervention without removing the dressing (Petkovska et al. 2024; Seo et al. 2024).

Beyond clinical applicators, the potential of pH responsive textile extended to sport performance tracking, environmental monitoring and personalized healthcare where real time feedback supports preventative medicine and lifestyle optimization.

CONCLUSIONS

This review provides a comprehensive analysis of recent advancements in wearable textile-based colorimetric pH sensors for non-invasive health monitoring. The findings highlight that progress in this domain is driven by advances in textile substrate pH-sensitive dyes and immobilization techniques, which collectively impact sensor performance, durability, and user comfort. Textile-based sensors have evolved from simple dye-treated fabrics to sophisticated hybrid systems integrating microfluidics, nanofibers, and biocompatible coatings. These innovations have enhanced mechanical flexibility, sensing accuracy, and incremental stability, establishing textiles as viable platforms for continuous physiological monitoring. The integration of natural and synthetic halochromic dyes provides complementary advantages, combining sustainability and biocompatibility with improved optical stability and broader pH sensitivity. However, despite significant progress, key challenges remain. Dye leaching, calibration drift, and mechanical degradation continue to limit long-term reliability. To address these issues, future efforts should prioritize hybrid immobilization methods, surface functionalization, and eco-friendly polymer systems that enhance dye retention and sensor reusability. Furthermore, standardized calibration frameworks and AI-assisted analysis are required to transform subjective visual sensing into objective, quantitative diagnostics. Looking forward, the convergence of smart textiles, digital imaging, and machine learning offers a pathway toward next-generation wearable diagnostics. Such systems could enable continuous, real-time health assessment through everyday clothing, empowering personalized healthcare, early disease detection, and preventive wellness management. Ultimately, textile-based colorimetric pH sensors represent a crucial step toward affordable, sustainable, and non-invasive health monitoring technologies, with the potential to bridge materials science, textile engineering, and digital health into an integrated, human-centered sensing system.

Some key findings from this review are as follows:

1. Textile-based colorimetric pH sensor performance is significantly influenced by material choice and functionalization, including user wearability, which impacts stability, durability, and accuracy.
2. Cotton remains the preferred substrate for wearable pH sensors due to its biocompatibility, moisture-absorption properties, and flexibility. The limitations that persist include pH-sensitive dye leaching and stability over prolonged periods. Hence, surface functionalization methods are often employed to improve sensor performance.
3. The balance between hydrophilic and mechanical properties is critical for wearable applications to ensure efficient biofluid absorption and durability against body movements.
4. The stability and reversibility of halochromic dyes, such as anthocyanins and curcumin, are essential for consistent color transitions and long-term usability under environmental conditions.
5. Advances in fabrication methods, including electrospinning, sol-gel processes, and microfluidic integration, enhance sensor sensitivity, specificity, and real-time biomarker monitoring.
6. Colorimetric pH sensors play a vital role in health monitoring, particularly in sweat analysis, enabling real-time detection of conditions such as cystic fibrosis, dehydration, and wound healing.

OUTLOOKS

Future innovations may focus on hydrophobic materials for enhanced durability, dual sensing mechanisms that integrate colorimetric and electrochemical methods for improved accuracy, and multi-analyte detection for thorough health monitoring. In this context, the incorporation of natural anthocyanin dyes offers an eco-friendly and biocompatible colorimetric approach, aligning with the trend toward sustainable and safe materials in wearable pH sensing.

REFERENCES

1. Abdelrahman, MS, Fouda, MMG, Ajarem, JS, Maodaa, SN, Allam, AA & Khattab, TA 2020, ‘Development of colorimetric cotton swab using molecular switching hydrazone probe in calcium alginate’, *Journal of Molecular Structure*, vol. 1216.
2. Agarwal, A, Raheja, A, Natarajan, TS & Chandra, TS 2012, ‘Development of universal pH sensing electrospun nanofibers’, *Sensors and Actuators, B: Chemical*, vol. 161, no. 1, pp. 1097–1101.
3. Alaysuy, O, Snari, RM, Alfi, AA, Aldawsari, AM, Abu-Melha, S, Khalifa, ME & El-Metwaly, NM 2022, ‘Development of green and sustainable smart biochromic and therapeutic bandage using red cabbage (Brassica oleracea L. Var. capitata) extract encapsulated into alginate nanoparticles’, *International Journal of Biological Macromolecules*, vol. 211, no. April, pp. 390–399.
4. Alehosseini, A, Gómez-Mascaraque, LG, Martínez-Sanz, M & López-Rubio, A 2019, ‘Electrospun curcumin-loaded protein nanofiber mats as active/bioactive coatings for food packaging applications’, *Food Hydrocolloids*, vol. 87, no. September 2018, pp. 758–771.
5. Alisaac, A, Alsahag, M, Alshareef, M, Snari, RM, Alhasani, M, Abumelha, HM & El-Metwaly, NM 2022, ‘Development of smart cotton fabrics immobilized with anthocyanin and potassium alum for colorimetric detection of bacteria’, *Inorganic Chemistry Communications*, vol. 145, no. August.
6. Azeem, M, Shahid, M, Masin, I & Petru, M 2024, ‘Design and development of textile-based wearable sensors for real-time biomedical monitoring; a review’, *Journal of the Textile Institute*.
7. Bamfield, P & Hutchings 2010, ‘Chromic Phenomena: the technological applications of color chemistry. Royal Society of Chemistry’, , pp. 1–50.
8. Bandodkar, AJ, Jeang, WJ, Ghaffari, R & Rogers, JA 2019, ‘Wearable Sensors for Biochemical Sweat Analysis’, *Annual Review of Analytical Chemistry*, vol. 12, pp. 1–22.
9. Bandodkar, AJ, Jeerapan, I & Wang, J 2016, ‘Wearable Chemical Sensors: Present Challenges and Future Prospects’, *ACS Sensors*, vol. 1, no. 5, pp. 464–482.
10. Boeva, Z, Mousavi, Z, Sokalski, T & Bobacka, J 2024, ‘Trends in Analytical Chemistry Recent trends in non-invasive on-body chemical sensing’, *Trends in Analytical Chemistry*, vol. 172, no. December 2023.
11. Caldara, M, Colleoni, C, Galizzi, M, Guido, E, Re, V, Rosace, G & Vitali, A 2012, ‘Low power textile-based wearable sensor platform for pH and temperature monitoring with wireless battery recharge’, *Proceedings of IEEE Sensors*, pp. 4–7.
12. Caldara, M, Colleoni, C, Guido, E, Re, V & Rosace, G 2016, ‘Optical monitoring of sweat pH by a textile fabric wearable sensor based on covalently bonded litmus-3-glycidoxypropyltrimethoxysilane coating’, *Sensors and Actuators, B: Chemical*, vol. 222, pp. 213–220.
13. Caldara, M, Colleoni, C, Guido, E, Re, V, Rosace, G & Vitali, A 2012, ‘Textile based colorimetric pH sensing - A platform for future wearable pH monitoring’, *Proceedings - BSN 2012: 9th International Workshop on Wearable and Implantable Body Sensor Networks*, pp. 11–16.
14. Câmara, JS, Locatelli, M, Pereira, JAM, Oliveira, H, Arlorio, M, Fernandes, I, Perestrelo, R, Freitas, V & Bordiga, M 2022, ‘Behind the Scenes of Anthocyanins—From the Health Benefits to Potential Applications in Food, Pharmaceutical and Cosmetic Fields’, *Nutrients*, vol. 14, no. 23.
15. Choudhry, NA, Arnold, L, Rasheed, A, Khan, IA & Wang, L 2021, ‘Textronics—A Review of Textile-Based Wearable Electronics’, *Advanced Engineering Materials*, vol. 23, no. 12, pp. 1–19.
16. Chung, M, Skinner, WH, Robert, C, Campbell, CJ, Rossi, RM, Koutsos, V & Radacsi, N 2021, ‘Fabrication of a Wearable Flexible Sweat pH Sensor Based on SERS-Active Au/TPU Electrospun Nanofibers’, *ACS Applied Materials and Interfaces*, vol. 13, no. 43, pp. 51504–51518.
17. Cui, L, Hu, J jing, Wang, W, Yan, C, Guo, Y & Tu, C 2020, ‘Smart pH response flexible sensor based on calcium alginate fibers incorporated with natural dye for wound healing monitoring’, *Cellulose*, vol. 27, no. 11, pp. 6367–6381.
18. Devarayan, K & Kim, BS 2015, ‘Reversible and universal pH sensing cellulose nanofibers for health monitor’, *Sensors and Actuators, B: Chemical*, vol. 209, pp. 281–286.
19. Di Costanzo, L & Panunzi, B 2021, ‘Visual pH sensors: From a chemical perspective to new bioengineered materials’, *Molecules*, vol. 26, no. 10.
20. Diculescu, VC, Beregoi, M, Evanghelidis, A, Negrea, RF, Apostol, NG & Enculescu, I 2019, ‘Palladium/palladium oxide coated electrospun fibers for wearable sweat pH-sensors’, *Scientific Reports*, vol. 9, no. 1, pp. 1–12.
21. El-Sedik, MS, Hemdan, BA, Hashem, MM, Aysha, TS, Mousa, AA, Youssef, YA & El-Naggar, ME 2024, ‘Bactericidal action of cost-effective colorimetric acid-base sensor of dyed cotton-based fabrics as a promising wound dressing mat’, *Journal of Photochemistry and Photobiology A: Chemistry*, vol. 456, no. April.
22. Falk, M, Psotta, C, Cirovic, S & Shleev, S 2020, ‘Non-invasive electrochemical biosensors operating in

human physiological fluids', *Sensors (Switzerland)*, vol. 20, no. 21, pp. 1–28.

23. Feldman, I 1956, 'Use and Abuse of pH Measurements', *Analytical Chemistry*, vol. 28, no. 12, pp. 1859–1866.
24. Ghadge, S, Marathe, A, Adivarekar, R & More, S 2024, 'Woolitmus: An Approach to Minimize E-waste by Using Wool-Based Wearable Sensor for Sweat pH Detection', *Fibers and Polymers*, vol. 25, no. 9, pp. 3379–3386.
25. Ghazal, H & Elshamy, M 2024, 'Ecofriendly finishing and Dyeing of textile using bioactive agents derived from plant extracts and waste', *Journal of Textiles, Coloration and Polymer Science*, vol. 21, no. Special Issue, pp. 83–104.
26. Guinovart, T, Valdés-Ramírez, G, Windmiller, JR, Andrade, FJ & Wang, J 2014, 'Bandage-Based Wearable Potentiometric Sensor for Monitoring Wound pH', *Electroanalysis*, vol. 26, no. 6, pp. 1345–1353.
27. Gupta, GK, Chahal, J & Bhatia, M 2015, 'Clitoria ternatea (L.): Old and new aspects', *Journal of Pharmacy Research*, vol. 3, no. January 2010, pp. 2610–2614.
28. Ha, JH, Jeong, Y, Ahn, J, Hwang, S, Jeon, S, Kim, D, Ko, J, Kang, B, Jung, Y, Choi, J, Han, H, Gu, J, Cho, S, Kim, H, Bok, M, Park, SA, Jeong, JH & Park, I 2023, 'A wearable colorimetric sweat pH sensor-based smart textile for health state diagnosis', *Materials Horizons*, vol. 10, no. 10, pp. 4163–4171.
29. Haddar, W, Ben Ticha, M, Meksi, N & Guesmi, A 2018, 'Application of anthocyanins as natural dye extracted from Brassica oleracea L. var. capitata f. rubra: dyeing studies of wool and silk fibres', *Natural Product Research*, vol. 32, no. 2, pp. 141–148.
30. Hatamie, A, Angizi, S, Kumar, S, Pandey, CM, Simchi, A, Willander, M & Malhotra, BD 2020, 'Review—Textile Based Chemical and Physical Sensors for Healthcare Monitoring', *Journal of The Electrochemical Society*, vol. 167, no. 3, p. 037546.
31. Heikenfeld, J, Jajack, A, Rogers, J, Gutruf, P, Tian, L, Pan, T, Li, R, Khine, M, Kim, J, Wang, J & Kim, J 2018, 'Wearable sensors: Modalities, challenges, and prospects', *Lab on a Chip*, vol. 18, no. 2, pp. 217–248.
32. Heng, W, Yang, G, Kim, WS & Xu, K 2022, 'Emerging wearable flexible sensors for sweat analysis', *Bio-Design and Manufacturing*, vol. 5, no. 1, pp. 64–84.
33. Hong, T, Choi, YK, Lim, T, Seo, K, Jeong, SM & Ju, S 2021, 'Elastic Halochromic Fiber as a Reversible pH Sensor', *Advanced Materials Technologies*, vol. 6, no. 3, pp. 1–10.
34. Houghton, A, Appelhagen, I & Martin, C 2021, 'Natural Blues : Structure Meets Function in Anthocyanins', , pp. 1–22.
35. Jankowska, DA, Bannwarth, MB, Schulenburg, C, Faccio, G, Maniura-Weber, K, Rossi, RM, Scherer, L, Richter, M & Boesel, LF 2017, 'Simultaneous detection of pH value and glucose concentrations for wound monitoring applications', *Biosensors and Bioelectronics*, vol. 87, pp. 312–319.
36. Jia, J, Liu, W, Xiao, Q, Yang, Y, Chen, J, Li, H, Fang, X & Li, Y 2023, 'Smart pH indicating functional fabric based on reversible acidichromic self-colored microparticles', *Progress in Organic Coatings*, vol. 185, no. August.
37. Karastathi, N, Salmane, AK & Parker, B 2024, 'pH-Responsive textile with anthocyanin-laden hydrogel yarns : a colorimetric and feasibility study',.
38. Koh, E & Hong, KH 2017, 'Functional fabric treatment using tannic acid and extract from purple-fleshed sweet potato', *Textile Research Journal*, vol. 87, no. 7, pp. 790–798.
39. Kuswandi, B, Andriani, N & Nugraha, AS 2022, 'Simple monitoring of pH and urea in whole blood using wearable smart woman pad', *BioImpacts*, vol. 12, no. 1, pp. 43–50.
40. Kuswandi, B, Irsyad, LH & Puspaningtyas, AR 2023, 'Cloth-based microfluidic devices integrated onto the patch as wearable colorimetric sensors for simultaneous sweat analysis', *BioImpacts*, vol. 13, no. 4, pp. 347–353.
41. Laffitte, Y & Gray, BL 2021, 'Real-Time potentiometric pH-sensor using a screen-printable polyaniline composite on textiles', *FLEPS 2021 - IEEE International Conference on Flexible and Printable Sensors and Systems*, pp. 3–6.
42. Lowry, JB & Chew, L 1974, 'On the use of extracted anthocyanin as a food dye', *Economic Botany*, vol. 28, no. 1, pp. 61–62.
43. Magnaghi, LR, Zanoni, C, Alberti, G & Biesuz, R 2024, 'pH sensors', in *Sensory Polymers: From their Design to Practical Applications*, pp. 587–631.
44. Manjakkal, L, Dervin, S & Dahiya, R 2020, 'Flexible potentiometric pH sensors for wearable systems', *RSC Advances*, vol. 10, no. 15, pp. 8594–8617.
45. Mao, P, Li, H & Yu, Z 2023, 'A Review of Skin-Wearable Sensors for Non-Invasive Health Monitoring Applications', *Sensors*, vol. 23, no. 7.
46. Marczewska, B & Marczewski, K 2010, 'First glass electrode and its creators F. haber and Z. klemensiewicz - on 100th anniversary', *Zeitschrift fur Physikalische Chemie*, vol. 224, no. 5, pp. 795–

799.
47. McCaul, M, Glennon, T & Diamond, D 2017, ‘Challenges and opportunities in wearable technology for biochemical analysis in sweat’, *Current Opinion in Electrochemistry*, vol. 3, no. 1, pp. 46–50.
48. Mei, X, Yang, J, Liu, J & Li, Y 2023, ‘Wearable, nanofiber-based microfluidic systems with integrated electrochemical and colorimetric sensing arrays for multiplex sweat analysis’, *Chemical Engineering Journal*, vol. 454, no. November 2022, pp. 25–28.
49. De Meyer, T, Hemelsoet, K, Van Speybroeck, V & De Clerck, K 2014, ‘Substituent effects on absorption spectra of pH indicators: An experimental and computational study of sulfonphthaleine dyes’, *Dyes and Pigments*, vol. 102, pp. 241–250.
50. De Meyer, T, Steyaert, I, Hemelsoet, K, Hoogenboom, R, Van Speybroeck, V & De Clerck, K 2016, ‘Halochromic properties of sulfonphthaleine dyes in a textile environment: The influence of substituents’, *Dyes and Pigments*, vol. 124, pp. 249–257.
51. Morris, D, Coyle, S, Wu, Y, Lau, KT, Wallace, G & Diamond, D 2009, ‘Bio-sensing textile based patch with integrated optical detection system for sweat monitoring’, *Sensors and Actuators, B: Chemical*, vol. 139, no. 1, pp. 231–236.
52. Mugo, SM & Zhang, Q 2019, *Nano-Sized Structured Platforms for Facile Solid-Phase Nanoextraction for Molecular Capture and (Bio)Chemical Analysis*, Elsevier Inc.
53. Park, JB, Kim, SH & Bae, JS 2011, ‘Quinaldine and Indole based pH sensitive Textile chemosensor’, *Fibers and Polymers*, vol. 12, no. 5, pp. 696–699.
54. Parlak, O, Curto, VF, Ojeda, E, Basabe-Desmonts, L, Benito-Lopez, F & Salleo, A 2019, ‘Wearable biosensors and sample handling strategies’, *Wearable Bioelectronics*, pp. 65–88.
55. Pars, A & Karadag, R 2024, ‘Sustainable Bio-Dyeing of Cellulosic-Based Fabrics with Anthocyanins from Black Carrot (Daucus carota L.)’, *Fibres and Textiles in Eastern Europe*, vol. 32, no. 3, pp. 50–56.
56. Peila, R, Varesano, A, Vineis, C, Bobba, V, Bobba, J, Piriou, A & Barazzotto, M 2021, ‘Fabric dyeing with colorimetric pH-responsive colours’, *Coloration Technology*, vol. 137, no. 2, pp. 123–133.
57. Petkovska, J, Geskovski, N, Marković, D, Dimova, V, Mirakovski, D, Radetić, M & Jordanov, I 2024, ‘Chitosan-pectin multilayer coating with anthocyanin grape dye as pH indicating wound dressing: Synthesis and characterization’, *Carbohydrate Polymer Technologies and Applications*, vol. 7, no. January.
58. Pour, SRS, Calabria, D, Emamiamin, A, Lazzarini, E, Pace, A, Guardigli, M, Zangheri, M & Mirasoli, M 2024, ‘Microfluidic-Based Non-Invasive Wearable Biosensors for Real-Time Monitoring of Sweat Biomarkers’, *Biosensors*, vol. 14, no. 1.
59. Pourreza, N & Golmohammadi, H 2015, ‘Application of curcumin nanoparticles in a lab-on-paper device as a simple and green pH probe’, *Talanta*, vol. 131, pp. 136–141.
60. Promphet, N, Hinestroza, JP, Rattanawaleedirojn, P, Soatthiyanon, N, Siralertmukul, K, Potiyaraj, P & Rodthongkum, N 2020, ‘Cotton thread-based wearable sensor for non-invasive simultaneous diagnosis of diabetes and kidney failure’, *Sensors and Actuators, B: Chemical*, vol. 321, no. July.
61. Promphet, N, Rattanawaleedirojn, P, Siralertmukul, K, Soatthiyanon, N, Potiyaraj, P, Thanawattano, C, Hinestroza, JP & Rodthongkum, N 2019, ‘Non-invasive textile based colorimetric sensor for the simultaneous detection of sweat pH and lactate’, *Talanta*, vol. 192, no. September 2018, pp. 424–430.
62. Promphet, N, Ummartyotin, S, Ngeontae, W, Puthongkham, P & Rodthongkum, N 2021, ‘Non-invasive wearable chemical sensors in real-life applications’, *Analytica Chimica Acta*, vol. 1179.
63. Punyachareonnon, Deerattrakul, V & Luepong, K 2021, ‘The Influence of pH, Temperature and Time on Dyeing of Silk Fabric by Black Bean Anthocyanin-rich Extract as Colorant’, *Progress in Color, Colorants and Coatings*, vol. 14, no. 3, pp. 179–186.
64. Rao, PS & Seshadri, TR 1943, ‘The structural chemistry of naturally occurring flavones and flavonols’, *Proceedings of the Indian Academy of Sciences - Section A*, vol. 17, no. 4, pp. 119–141.
65. Ribeiro, AI, Vieira, B, Alves, C, Silva, B, Pinto, E, Cerqueira, F, Silva, R, Remião, F, Shvalya, V, Cvelbar, U, Padrão, J, Dias, AM & Zille, A 2023, ‘Halochromic Silk Fabric as a Reversible pH-Sensor Based on a Novel 2-Aminoimidazole Azo Dye’, *Polymers*, vol. 15, no. 7.
66. Rosace, G, Guido, E, Colleoni, C, Brucale, M, Piperopoulos, E, Milone, C & Plutino, MR 2017, ‘Halochromic resorufin-GPTMS hybrid sol-gel: Chemical-physical properties and use as pH sensor fabric coating’, *Sensors and Actuators, B: Chemical*, vol. 241, pp. 85–95.
67. Roy, S & Rhim, J 2021, ‘Anthocyanin food colorant and its application in pH-responsive color change indicator films’, *Critical Reviews in Food Science and Nutrition*, vol. 0, no. 0, pp. 1–29.
68. Salaün, F 2023, ‘SMART TEXTILE pH SENSOR BASED ON CURCUMIN MICROCAPSULES’, *Tekstil ve Muhendis*, vol. 30, no. 132, pp. 310–317.
69. Saldanha, DJ & Dorval Courchesne, NM 2025, ‘Coating of Threads with Fluorescent Curli Fibers for pH Sensing’, *ACS Applied Bio Materials*, vol. 8, no. 1, pp. 225–235.
70. Schoolaert, E, Hoogenboom, R & De Clerck, K 2017, ‘Colorimetric Nanofibers as Optical Sensors’,

Advanced Functional Materials, vol. 27, no. 38, pp. 1–26.

71. Van der Schueren, L 2008, 'pH-sensitieve textielmaterialen als nieuwe textielsensoren',.
72. van der Schueren, L & de Clerck, K 2011, 'Textile materials with a pH-sensitive function', *International Journal of Clothing Science and Technology*, vol. 23, no. 4, pp. 269–274.
73. Van Der Schueren, L, Mollet, T, Ceylan, Ö & De Clerck, K 2010, 'The development of polyamide 6.6 nanofibres with a pH-sensitive function by electrospinning', *European Polymer Journal*, vol. 46, no. 12, pp. 2229–2239.
74. Seo, HS, Lim, H, Lim, T, Seo, K, Yang, J, Kang, Y, Han, SJ, Ju, S & Jeong, SM 2024, 'Facile and cost-effective fabrication of wearable alpha-naphtholphthalein-based halochromic sensor for wound pH monitoring', *Nanotechnology*, vol. 35, no. 24.
75. Seshadri, DR, Li, RT, Voos, JE, Rowbottom, JR, Alfes, CM, Zorman, CA & Drummond, CK 2019, 'Wearable sensors for monitoring the internal and external workload of the athlete', *npj Digital Medicine*, vol. 2, no. 1.
76. Sigurdson, GT & Giusti, MM 2014, 'Bathochromic and hyperchromic effects of aluminum salt complexation by anthocyanins from edible sources for blue color development', *Journal of Agricultural and Food Chemistry*, vol. 62, no. 29, pp. 6955–6965.
77. Snari, RM, Alsahag, M, Alisaac, A, Bayazeed, A, Alsoliemy, A, Khalifa, ME & El-Metwaly, NM 2022, 'Smart textiles immobilized with hydrazone probe for colorimetric recognition of bacteria', *Journal of Molecular Liquids*, vol. 366.
78. Tasangtong, B, Sirichan, K, Hasoon, C, Na Nongkhai, P, Rodthongkum, N & Sameenoi, Y 2024, 'Fabrication of biocompatible and biodegradable cloth-based sweat sensors using polylactic acid (PLA) via stencil transparent film-printing', *Sensors and Actuators B: Chemical*, vol. 408, no. December 2023.
79. Wang, H, Tang, Z & Zhou, W 2016, 'A method for dyeing cotton fabric with anthocyanin dyes extracted from mulberry (Morus rubra) fruits', *Coloration Technology*, vol. 132, no. 3, pp. 222–231.
80. Wang, K, Liu, W, Wu, J, Li, H, Peng, H, Zhang, J, Ding, K, Wang, X, Hou, C, Zhang, H & Luo, Y 2025, 'Smart Wearable Sensor Fuels Noninvasive Body Fluid Analysis', *ACS Applied Materials and Interfaces*.
81. Wang, R, Zhai, Q, Zhao, Y, An, T, Gong, S, Guo, Z, Shi, QQ, Yong, Z & Cheng, W 2020, 'Stretchable gold fiber-based wearable electrochemical sensor toward pH monitoring', *Journal of Materials Chemistry B*, vol. 8, no. 16, pp. 3655–3660.
82. Xi, P, He, X, Fan, C, Zhu, Q, Li, Z, Yang, Y, Du, X & Xu, T 2023, 'Smart Janus fabrics for one-way sweat sampling and skin-friendly colorimetric detection', *Talanta*, vol. 259, no. January, pp. 1–7.
83. Xiao, G, He, J, Qiao, Y, Wang, F, Xia, Q, Wang, X, Yu, L, Lu, Z & Li, CM 2020, 'Facile and Low-Cost Fabrication of a Thread/Paper-Based Wearable System for Simultaneous Detection of Lactate and pH in Human Sweat', *Advanced Fiber Materials*, vol. 2, no. 5, pp. 265–278.
84. Xu, Z, Qiao, X, Tao, R, Li, Y, Zhao, S, Cai, Y & Luo, X 2023, 'A wearable sensor based on multifunctional conductive hydrogel for simultaneous accurate pH and tyrosine monitoring in sweat', *Biosensors and Bioelectronics*, vol. 234, no. April.
85. Yang, L, Yuan, QY, Lou, CW, Lin, JH & Li, TT 2024, 'Recent advances on pH-responsive polymers integrated with nature colorants: from preparation to applications', *Textile Research Journal*.
86. Yang, X, Chawang, K & Chiao, JC 2019, 'Wearable Iridium Oxide pH Sensors for Sweat pH Measurements', *Proceedings of IEEE Sensors*, vol. 2019- Octob.
87. Yang, YL, Chuang, MC, Lou, SL & Wang, J 2010, 'Thick-film textile-based amperometric sensors and biosensors', *Analyst*, vol. 135, no. 6, pp. 1230–1234.
88. Yao, H, Liu, H, Hou, Y, Gao, S & Hou, J 2025, 'Electro-blown spinning of hygroscopic breathable fabrics with patterned antisymmetrical wettability for visualized health state diagnosis', *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, vol. 705, no. September 2024.
89. Yin, Y, Jia, J, Wang, T & Wang, C 2017, 'Optimization of natural anthocyanin efficient extracting from purple sweet potato for silk fabric dyeing', *Journal of Cleaner Production*, vol. 149, pp. 673–679.
90. Yu, W, Li, Q, Zhao, Z, Gong, J, Li, Z & Zhang, J 2023, 'A yarn/fabric-based microfluidic patch for sweat sensing and monitoring', *Journal of the Textile Institute*.
91. Zhang, J, Zou, X, Zhai, X, Huang, XW, Jiang, C & Holmes, M 2019, 'Preparation of an intelligent pH film based on biodegradable polymers and roselle anthocyanins for monitoring pork freshness', *Food Chemistry*, vol. 272, no. April 2018, pp. 306–312.
92. Zhang, L, Li, Z, Chang, R, Chen, Y & Zhang, W 2009, 'Synthesis and characterization of novel phenolphthalein immobilized halochromic fiber', *Reactive and Functional Polymers*, vol. 69, no. 4, pp. 234–239.
93. Zhang, X, Reagan, MR & Kaplan, DL 2009, 'Electrospun silk biomaterial scaffolds for regenerative medicine', *Advanced Drug Delivery Reviews*, vol. 61, no. 12, pp. 988–1006.
94. Zhao, K, Kang, B & Zhou, B 2022, 'Wearable electrochemical sensors for monitoring of inorganic ions

and pH in sweat', *International Journal of Electrochemical Science*, vol. 17.

95. Zhao, Z, Li, Q, Chen, L, Zhao, Y, Gong, J, Li, Z & Zhang, J 2021, 'A thread/fabric-based band as a flexible and wearable microfluidic device for sweat sensing and monitoring', *Lab on a Chip*, vol. 21, no. 5, pp. 916–932.
96. Zhou, J, Jiang, B, Gao, C, Zhu, K, Xu, W & Song, D 2022, 'Stable, reusable, and rapid response smart pH-responsive cotton fabric based on covalently immobilized with naphthalimide-rhodamine probe', *Sensors and Actuators B: Chemical*, vol. 355.
97. Zhou, L, Menon, SS, Li, X, Zhang, M & Malakooti, MH 2024, 'Machine Learning Enables Reliable Colorimetric Detection of pH and Glucose in Wearable Sweat Sensors', *Advanced Materials Technologies*, vol. 2401121, pp. 1–11.
98. Zhu, J, Nesr, N El, Simon, C, Rettenmaier, N, Beiler, K & Kao, HC 2023, 'BioWeave : Weaving Thread-Based Sweat-Sensing On-Skin Interfaces', in *UIST '23, October 29–November 01, 2023, San Francisco, CA, USA*.