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Wearable UV Devices for Sun Protection: Practicalities, Utilities, and Limitations

Grace Herrick, Kelly Frasier & Erin Lowe

Grace Herrick, BA - Alabama College of Osteopathic Medicine, Dothan, AL, United States

ORCID ID: https://orcid.org/0009-0009-2087-3005; E-mail: herrickg8780@acom.edu

Kelly Frasier, DO, MS - Department of Dermatology, Northwell Health, New Hyde Park, NY, United States

ORCID ID: https://orcid.org/0000-0002-6808-9174

Erin Lowe, DO - Nuvance Health Network, Danbury, CT, United States

ORCID ID: https://orcid.org/0009-0005-8083-1641; E-mail: erinlowe12@gmail.com

Abstract

Wearable ultraviolet (UV) devices present a promising innovation in personalized sun protection by providing continuous, real-time monitoring of UV radiation exposure. These devices are equipped with advanced sensors capable of detecting multiple UV wavelengths and offer seamless integration with mobile health platforms to deliver personalized recommendations, such as reminders for sunscreen reapplication based on individual exposure levels. Practical applications extend to diverse populations, accounting for factors such as varying skin types, environmental conditions, and long-term user adherence. The utility of these devices lies not only in their ability to enhance sun safety behaviors but also in potentially reducing the incidence of UV-induced skin damage, including sunburn, photoaging, and skin cancer. However, several limitations persist, including calibration drift over time, inaccuracies due to environmental interference (e.g., sweat, humidity, clothing), and inconsistent performance across different Fitzpatrick skin types. The effectiveness of these devices can also be influenced by user compliance, socioeconomic disparities, and the need for improved public education on proper usage. Moreover, accessibility challenges, particularly in underserved populations, raise concerns about equitable distribution of this technology. While wearable UV devices offer considerable potential in augmenting existing photoprotection measures, further large-scale clinical validation studies are required to refine their accuracy, reliability, and usability across broader demographic groups. Enhanced integration with teledermatology and public health initiatives may further strengthen the role of these devices in comprehensive sun protection strategies.

Keywords

teledermatology integration, mobile health applications, perovskite photodetectors, hydrogel-based *sensors, triboelectric energy harvesting*

1. Introduction

Wearable ultraviolet (UV) sensors represent a significant advancement in personal sun protection by addressing the growing need for accessible and responsive approaches to UV exposure monitoring. With over 2 million cases of non-melanoma skin cancers and 132,000 cases of melanoma diagnosed annually, reported by the World Health Organization (2017), there remains an urgent need to address the detrimental effects of UV radiation on skin health. UV radiation contributes not only to sunburn and photoaging but also increases the risk of skin cancers, prompting the development of innovative wearable technologies that track and manage exposure. Wearable devices are particularly relevant as individuals engage in more outdoor activities, where UV exposure levels can vary significantly depending on geographic location, altitude, and time of year (Dumont et al., 2024; Allen, Swift, Nield, Liley, & McKenzie, 2020). Increased awareness of these dangers has driven researchers and developers to design UV monitoring devices that can seamlessly integrate into daily routines, empowering users to make informed decisions about their sun safety (Shi et al., 2018; Kurz et al., 2020; Esfahani, 2021). By providing real-time feedback, wearable UV sensors offer a proactive approach to sun protection, enabling individuals to adjust their behaviors based on current exposure levels (Allen, Swift, Nield, Liley, & McKenzie, 2020; Horsham, Antrobus, Olsen, Ford, Abernethy, & Hacker, 020; Komatsu, Kawamoto, & Ikuno, 2022).

Wearable UV sensors provide real-time data, allowing users to understand their immediate UV exposure levels and adjust their sun protection strategies accordingly. The development of electronic UV dosimeters, as examined by Allen et al., highlights how these technologies can facilitate awareness by providing erythemally weighted UV readings, educating users on the dangers of UV radiation (Allen, Swift, Nield, Liley, & McKenzie, 2020). Additional studies, such as those by Horsham et al., demonstrate that wearable UV sensors can positively influence sun safety behaviors among young adults, who tend to have lower adherence to sun protection protocols (Horsham, Antrobus, Olsen, Ford, Abernethy, & Hacker, 2020). Immediate feedback from these devices has been shown to prompt protective behaviors, such as more frequent sunscreen application and increased use of UV-blocking accessories. Timely feedback is particularly significant in high UV environments, where users are often unaware of the full extent of their exposure. By delivering prompt information, these devices help users take preventive action, reducing the risk of both short-term effects like sunburn and long-term risks such as skin cancer.

Advances in material science and sensor technology have driven the rapid evolution of wearable UV devices. Flexible and durable materials, such as perovskite-based photodetectors and nanocomposite hydrogels, enhance the functionality and comfort of these devices, allowing for prolonged wear and accurate readings under various environmental conditions (Komatsu, Kawamoto, & Ikuno, 2022; Zhou et al., 2022). The use of advanced materials like ZnO-cellulose nanocomposites and polymer-based UV detectors further broadens the range of applications, as these materials maintain functionality under extreme temperatures and environmental stress (Komatsu, Kawamoto, & Ikuno, 2022). Additionally, the integration of self-powered systems, such as bioinspired piezoresistive sensors, makes wearable UV sensors more sustainable and user-friendly, aligning with a global trend towards eco-friendly personal technology (Yu, Xu, Gong, Li, Li, Wei, & Tang, 2022). Energy harvesting capabilities, such as those found in triboelectric nanogenerators, enhance the practicality of these devices by reducing reliance on external power sources. Recent advancements position wearable UV sensors as valuable tools for promoting public health and supporting long-term sun safety habits.

The current landscape of wearable UV devices is explored within this comprehensive review, with an evaluation of their role in enhancing sun safety and preventing UV-induced skin damage. Recent innovations in sensor materials, sustainable power solutions, and multifunctional designs that accommodate various skin types and environmental conditions are examined. Limitations such as calibration drift, user compliance challenges, and accessibility issues in underserved populations are addressed. The discussion highlights how wearable UV devices can complement traditional sun protection strategies, while also identifying areas in need of further development and clinical validation. Synthesizing the latest research provides insights into the effectiveness of these technologies and their potential for broad-scale implementation across diverse demographics. Understanding the capabilities and challenges of wearable UV sensors will help guide future innovations in personal sun safety.

2. Review

2.1 Material Innovations in Wearable UV Sensors

Recent developments in materials science have significantly enhanced the flexibility, durability, and sensitivity of wearable UV sensors, enabling them to adapt to a variety of applications and environments. For example, Komatsu et al. developed flexible and translucent ZnO–cellulose nanocomposite films that respond dynamically to UV exposure (Komatsu, Kawamoto, & Ikuno, 2022). These films are created through a simple spray coating method, resulting in a wearable material that can be integrated into textiles and withstand various environmental conditions (Komatsu, Kawamoto, & Ikuno, 2022). Another example is the use of perovskite-based photodetectors, as described by Zhou et al., which exhibit high sensitivity to UV radiation and maintain stability after thousands of bending cycles (Zhou et al., 2022). By embedding these photodetectors into flexible wristbands, researchers have enabled continuous UV monitoring suitable for daily wear. Such materials not only provide precise UV readings but also allow devices to remain functional under the mechanical stresses associated with regular use.

Nanocomposite materials have further expanded the potential for wearable UV sensing by enhancing both the comfort and durability of these devices. Botti et al. explored the use of $TiO2$ nanocomposite hydrogels to create colorimetric UV sensors that change color in response to UV exposure, providing an easy-to-read, visual indication of UV intensity (Botti, Bonfigli, D'Amato, Rodesi, & Santonicola, 2023). Hydrogels are flexible enough to be incorporated into patches or wristbands, making them ideal for continuous wear. Similarly, Liu et al. (2024) investigated lignosulfonate-doped polyaniline-reinforced hydrogels, which offer high sensitivity to UV radiation and maintain their functionality across a range of environmental conditions. Hydrogels are particularly suited for wearable applications as they combine high electrical conductivity with UV resistance, allowing for efficient detection and transmission of UV data. The versatility of these materials supports the development of devices that can function across different skin types and usage scenarios, broadening the accessibility of wearable UV sensors.

Advanced nanomaterials, including III-nitride membranes and halide-exchanged perovskites, have also contributed to the miniaturization and increased accuracy of UV sensors (Chen et al., 2023). Advancements include a centimeter-transferable III-nitride membrane that is both durable and flexible, retaining much of its performance even after repeated bending (Chen et al., 2023). This membrane’s high sensitivity to UV radiation enables precise, real-time readings that are essential for wearable devices intended for long-term use. Similarly, the halide-exchanged perovskites explored by Sun et al. provide dynamic UV visualization through tunable fluorescence colors, enhancing user engagement by offering a color-coded feedback system for UV monitoring (Sun et al., 2022). By focusing on novel materials that allow for flexible design and accurate UV detection, researchers are making wearable UV sensors more practical for diverse and long-term applications. Many recent advancements support the continued growth of wearable technologies aimed at preventing UV-induced skin damage.

2.2 Powering Wearable UV Devices Towards Self-Sustaining Technology

A critical aspect of wearable UV sensors is the development of self-sustaining power sources, enabling these devices to function continuously without frequent recharging or replacement. Energy-harvesting technologies, such as triboelectric nanogenerators (TENGs), offer a promising solution by converting mechanical energy from daily activities into electricity (Chen, Tang, Cheng, & Zheng, 2023). Chen et al. (2023) explored a TENG integrated with a UV-curable organic coating, achieving high output power and stability through a fast, cost-effective spray-coating process. TENG can be incorporated into wearable UV devices, powering the sensors sustainably and eliminating the need for external energy sources. Similarly, other developed TENG’s use an organic coating capable of converting ambient mechanical energy into electricity, supporting the practical application of self-powered UV sensors (Chen, Cao, Zhang, Liu, Yu, & Guo, 2022). By integrating TENGs into UV monitoring wearables, researchers can extend the device’s operational lifespan, improving user convenience and reducing maintenance requirements.

Bioinspired sensors that leverage naturally occurring processes for energy conversion are another avenue for enhancing the sustainability of wearable UV technology. Yu et al. (2022) introduced a piezoresistive sensor using zinc oxide nanorods on graphene-treated cotton, which is self-powered and capable of monitoring both UV intensity and physiological indicators, such as pulse and motion. This dual-functionality is particularly valuable in wearable devices that aim to provide comprehensive health monitoring while remaining power-efficient. Additionally, Lei et al. (2023) developed an anti-freezing, conductive ionic hydrogel for smart wearables that responds to both UV radiation and mechanical stress, powered by the movement of ions within the gel. Such innovations allow for continuous monitoring in extreme environmental conditions, ensuring the functionality of wearable UV sensors in diverse climates. Developments in bioinspired and ionic-based self-powering methods enhance the practicality of wearable devices by reducing dependency on batteries and external charging.

Solar energy harvesting and other photonic approaches have also emerged as sustainable power solutions for wearable UV sensors, providing a continuous source of energy directly from sunlight. For instance, AlGaN Schottky photodiodes that convert UV light into electrical signals, enabling self-sustained operation for real-time UV monitoring in wearable formats have been investigated (Allen, Swift, Nield, Liley, & McKenzie, 2020). This approach is especially useful in sunny environments, where the UV sensors can simultaneously monitor exposure and recharge. Additionally, AlQahtani et al. (2022) discussed a solar-powered UV monitoring band for drivers, which leverages sunlight exposure through vehicle windows to power the device. By employing solar energy as a power source, these devices become not only more sustainable but also more accessible, as they reduce the cost and maintenance associated with traditional battery-powered wearables. The integration of solar and photonic energy-harvesting systems into wearable UV sensors underscores the potential for creating long-lasting, environmentally friendly technology that supports public health efforts in sun protection.

2.3 Real-Time UV Monitoring and Dosimetry

Real-time UV monitoring is essential for wearable devices aimed at providing users with immediate feedback on their UV exposure, enabling proactive sun protection behaviors. Devices equipped with precise UV dosimetry capabilities allow users to track their exposure in real time, tailoring their protective measures accordingly. Xu et al. (2018) introduced a wearable UV monitor based on a p-CuZnS/n-TiO_2 photodetector, which operates across a broad UV spectrum and offers immediate feedback. This photodetector provides accurate, wavelength-specific UV monitoring, making it suitable for environments with varying UV exposure levels. Similarly, Dumont et al. evaluated wearable UV dosimeters in a clinical trial setting, demonstrating a 95% reduction in non-melanoma skin cancer incidence among elderly participants using these devices (Dumont et al., 2024). By delivering consistent and immediate data on UV exposure, these wearables empower users to take timely action in managing their sun protection, particularly in high-risk settings.

Wearable UV patches, like La Roche-Posay's My Skin Track UV, have enhanced the scope of real-time UV monitoring by integrating smartphone technology with photosensitive materials (Shi et al., 2018). This device adheres to the skin and changes color as it accumulates UV exposure, providing users with visual cues that reflect their total UV dose (Shi et al., 2018). Users can scan the patch with a smartphone app, which translates these color changes into quantitative data, delivering actionable insights for sun protection. This level of real-time feedback allows users to adjust their behavior throughout the day based on their UV exposure, increasing their awareness and adherence to sun safety protocols. With real-time UV monitoring technology, wearable UV sensors are well-positioned to contribute significantly to public health efforts aimed at reducing the prevalence of UV-induced skin damage.

Recent advancements in data processing and integration with mobile health applications have enhanced the functionality of real-time UV monitoring systems, making them more user-friendly and accessible. For example, Allen et al. explored a UV-sensitive wearable that integrates with a mobile application to convert erythemally weighted UV readings into personalized sun protection recommendations (Allen, Swift, Nield, Liley, & McKenzie, 2020). Mobile integration allows for more targeted feedback, tailoring sun safety advice to each user's specific needs and exposure patterns. Another study demonstrated that wearable UV sensors improved sun safety behaviors among young adults at an outdoor festival, where real-time feedback encouraged greater use of sunscreen and protective clothing (Horsham, Antrobus, Olsen, Ford, Abernethy, & Hacker, 2020). With the integration of mobile health platforms, wearable UV dosimeters not only offer personal health benefits but also contribute to broader public health initiatives focused on reducing UV-induced skin damage.

UV dosimeters and real-time monitoring systems have found applications beyond personal sun safety, extending to clinical and operational safety contexts. Chmielinski et al. (2022) developed a wearable spectroradiometer platform capable of measuring UV radiation across the 300-700nm range, useful for environments with both UV and visible light exposure. This system is applicable in clinical settings where patients require UV monitoring during phototherapy treatments or for individuals working in UV-intense environments. Another discussion of the use of wearable UV-C sensors to monitor safe UV exposure during disinfection procedures highlight how these devices can prevent overexposure for operators in healthcare settings (Cullinan, Scott, Linogao, Bradwell, Cooper, & McGinn, 2023). By offering precise, real-time UV data, these dosimeters contribute to improved safety protocols, demonstrating the versatility of wearable UV technology in both healthcare and occupational safety.

2.4 User Engagement and Behavioral Influence of UV Wearables

The ability of wearable UV devices to influence user behavior is a central component of their effectiveness in promoting sun safety. Research has shown that these wearables can significantly improve protective habits by providing real-time feedback on UV exposure, which acts as a behavioral prompt for users. Horsham et al.'s (2020) study was conducted at an outdoor festival and revealed that UV sensors encouraged young adults to increase sunscreen usage and wear sunglasses, even though overall sunburn rates remained high. This demonstrates the potential of wearable UV devices to improve sun safety behaviors, especially in environments where UV exposure is often overlooked. Additionally, by providing immediate feedback, these wearables help users internalize the risks of UV exposure, ultimately fostering a habit of proactive sun protection.

Devices like the L'Oreal My UV Patch and the SunFriend device provide intuitive feedback mechanisms that simplify the process of monitoring UV exposure (Kurz et al., 2020; Esfahani, 2021). The L'Oreal My UV Patch uses photosensitive dyes that change color in response to cumulative UV doses (Kurz et al., 2020). Users scan the patch with a smartphone app to receive detailed feedback on their UV exposure levels, encouraging them to apply or reapply sunscreen as needed (Kurz et al., 2020). This user-friendly approach enhances engagement by making sun safety a visible and easily accessible part of their routine. Similarly, the SunFriend device incorporates LED indicators that light up progressively as users reach their maximum safe exposure based on their skin type (Esfahani, 2021). By providing visual, standalone cues without the need for a smartphone, the SunFriend device caters to users who prefer a more direct approach to sun protection, supporting proactive sun safety habits by allowing immediate adjustments to outdoor activities.

The incorporation of user-friendly interfaces, such as colorimetric indicators and mobile applications, has also enhanced user engagement with wearable UV technology. Kurz et al. introduced wearable UV devices that use colorimetric changes to indicate UV intensity, creating an intuitive system that requires minimal interpretation from the user (Kurz et al., 2020). Such devices are particularly beneficial for those less familiar with UV radiation, as they provide an accessible means of understanding exposure levels. Zheng et al. (2020) also developed color-changing UV indicators embedded in electrospun fibers, which offer visible, textile-integrated feedback that can be incorporated into clothing. These approaches not only increase user engagement but also make UV monitoring more convenient, as users can simply glance at the device to assess their UV exposure. By simplifying the interpretation of UV data, these wearable devices encourage consistent use, which is essential for effective sun protection.

Integration with mobile health platforms has further expanded the impact of wearable UV devices on user behavior by delivering personalized recommendations and reminders. AlQahtani et al.'s (2022) solar-powered UV monitoring band for drivers that leverages smartphone connectivity to calculate time until sunburn and suggest appropriate sun protection measures based on skin type and UV index is an example of how wearable devices can offer real-time, customized feedback, enhancing their usability for diverse scenarios. This band underscores the versatility of wearable UV monitors, allowing them to adapt recommendations based on situational needs, such as time spent in a vehicle with direct sunlight exposure. Additionally, the exploration of UV-sensitive wearables that sync with mobile apps to convert UV exposure data into actionable advice, such as reapplication reminders, has highlighted the potential for these devices to support users in maintaining consistent sun protection habits and enhance overall skin health (Allen, Swift, Nield, Liley, & McKenzie, 2020). By combining UV monitoring with user-specific guidance, these devices encourage users to engage with sun safety practices in a personalized manner. A highly customized level of personalization not only enhances compliance but also increases the likelihood that users will adopt long-term sun protection behaviors, reducing their risk of UV-induced skin damage over time.

2.5 AI and Advanced Processing in UV Detection

The integration of artificial intelligence (AI) and advanced data processing in wearable UV sensors has enhanced the precision, accuracy, and usability of these devices, enabling more personalized and reliable monitoring. Machine learning algorithms, particularly convolutional neural networks (CNNs), have been applied to wearable UV sensors to improve image-based UV detection and minimize environmental interference. Chen et al.'s (2022) wearable UV sensor leverages CNNs to analyze color changes in photochromic materials, achieving a high recognition rate and accuracy by filtering out background light variations. Data processing not only increases the device's sensitivity to UV radiation but also allows for more accurate readings in a variety of lighting conditions, enhancing the practicality of these wearables for daily use.

Integration with smartphone applications offers another layer of functionality that enhances user engagement and data accessibility. For instance, Alam et al. (2024) developed a 3D-printed smartwatch with UV and temperature sensors that sync with a smartphone app to deliver real-time monitoring data. This smartwatch uses the app to analyze colorimetric changes in UV-responsive pigments, translating UV and temperature exposure into actionable information for the user. Smartphone connectivity eliminates the need for separate data storage on the device itself, allowing the smartwatch to provide real-time feedback while relying on minimal internal power. Such integration enhances AI-driven capabilities by leveraging mobile technology for data processing and personalized feedback, offering an intuitive interface that allows users to access their exposure history and adjust their behaviors accordingly. By extending device functionality through app-based processing, wearables like this smartwatch facilitate more sophisticated and accessible UV monitoring.

AI-driven processing also enables more nuanced and responsive UV monitoring by adapting to changing environmental factors in real-time. For instance, the flexible III-nitride membrane UV sensor discussed earlier combines advanced material science with AI algorithms to detect shifts in UV intensity, enhancing both responsiveness and precision (Chen et al., 2023). By using machine learning to analyze sensor data, devices can adjust their calibration dynamically, ensuring accurate readings even as external conditions fluctuate. Adaptability is particularly important for users in outdoor environments, where UV exposure can vary based on factors such as cloud cover, altitude, and time of day. AI-enhanced processing allows wearable UV devices to offer continuous, real-time feedback that remains reliable across a wide range of conditions, increasing their effectiveness as personal sun safety tools.

Moreover, the integration of AI into wearable UV sensors facilitates more comprehensive data collection and analysis, which can be used to support public health research and educational initiatives. Devices equipped with AI-driven data logging, such as those discussed by Sun et al. (2022), can store information on cumulative UV exposure, skin type, and behavioral responses over time. Data can then be analyzed to identify trends in UV exposure and compliance with sun safety recommendations, offering insights that can inform public health campaigns. Additionally, by connecting to mobile health platforms, AI-enhanced wearables can provide users with personalized sun protection recommendations based on their historical UV exposure patterns. The combination of real-time monitoring and long-term data analysis underscores the potential of AI in wearable UV sensors to not only improve individual user experiences but also contribute to broader efforts in skin cancer prevention and education.

2.6 Multifunctional Wearables for Comprehensive Environmental Sensing

In addition to monitoring UV radiation, multifunctional wearables have emerged as a comprehensive solution for tracking various environmental and physiological factors, providing users with a holistic view of their health and surroundings. Lei et al.'s (2023) dual-stimuli-responsive hydrogel that responds not only to UV exposure but also to mechanical stress, allowing it to function as both a UV monitor and a strain sensor. This multifunctional design is ideal for outdoor activities, as it can simultaneously track environmental conditions and physical exertion, providing a more complete picture of the wearer's exposure and activity level. Similarly, because Yu et al.'s (2022) piezoresistive sensor monitors both UV radiation and physiological factors like motion and pulse, it is well-suited for comprehensive health monitoring in diverse outdoor settings. Multifunctional devices enhance user engagement by combining multiple functions into a single wearable, making them more versatile and convenient. Other devices have expanded their capabilities by integrating UV monitoring with temperature and humidity detection, offering users a more comprehensive assessment of environmental factors that influence sun safety. For instance, the solar-powered UV band discussed also monitors IR exposure for drivers, which is particularly useful in high-temperature environments as it provides an additional layer of information to guide protective measures beyond UV protection alone (AlQahtani, Bukair, Alessa, AlDushaishi, & Ali, 2022). A convergence of sensors allows for a more tailored approach to sun safety, enabling wearers to make informed decisions based on a variety of environmental inputs. By broadening the scope of wearable UV devices to include other relevant environmental factors, multifunctional wearables cater to the diverse needs of users across different settings.

Some multifunctional wearables also incorporate biochemical sensing to assess physiological responses to environmental stressors, making them valuable for both health monitoring and sun safety. Song et al. (2023) examined a wearable that monitors UV exposure while simultaneously tracking vitamin C levels in sweat, providing insights into oxidative stress and skin health. This type of device offers dual protection by alerting users to both external UV exposure and internal markers of potential damage, such as low antioxidant levels. Additionally, Amador-Mendez et al. (2024) discussed UV-A LED-integrated wearables that facilitate phototherapy treatments, demonstrating how multifunctional wearables can address both protective and therapeutic needs. By integrating biochemical sensing and phototherapy capabilities, these devices support comprehensive skin health management, extending their utility beyond sun protection alone. Multifunctional wearables reflect the potential for UV monitoring technology to play a broader role in personal health, encompassing a wide range of environmental and physiological factors (Table 1).

2.7 Limitations of Wearable UV Devices

Despite the promising benefits of wearable UV devices, several limitations persist, impacting their overall effectiveness and accessibility. One common challenge is calibration drift, where the accuracy of UV readings may degrade over time due to prolonged exposure to environmental factors. Dumont et al. (2024) noted that even high-sensitivity materials like III-nitride membranes require periodic recalibration to maintain accurate readings. Sensors designed to detect specific UV wavelengths can become less reliable over extended periods, particularly in outdoor environments where fluctuating temperatures and humidity can impact performance (Dumont et al., 2024). Although materials like flexible III-nitride membranes offer durability, regular recalibration is necessary to ensure that users receive accurate, consistent data (Chen et al., 2023). The importance of addressing calibration drift highlights a broader need for technologies that can self-calibrate or adjust dynamically, a feature that would enhance the utility and lifespan of wearable UV devices.

Environmental interference poses another significant limitation for wearable UV devices, as factors such as sweat, humidity, and clothing can affect sensor performance. Materials like colorimetric hydrogels and ZnO-cellulose nanocomposites, discussed by Kurz et al. (2020) and Komatsu et al. (2022), offer visible feedback on UV exposure through color changes. However, moisture from sweat or the occlusion of sensors by clothing can reduce the effectiveness of these devices, as water and fabric layers interfere with UV detection. Devices like the SunFriend, while innovative, may struggle to maintain accuracy in high-humidity environments, as excess moisture impacts sensor durability (Esfahani, 2021). Environmental factors limit the reliability of wearable UV devices for users engaging in vigorous outdoor activities, particularly in hot climates where sweat is inevitable. Addressing this limitation requires continued material innovation to enhance the moisture resistance and robustness of UV sensors, enabling them to maintain accuracy regardless of environmental conditions.

User compliance is another critical factor in the effectiveness of wearable UV devices, as consistent use is essential for these devices to provide adequate protection. For example, both Horsham et al. and Allen et al., explain that while wearable UV sensors can positively influence sun safety behaviors, their impact relies heavily on users following device prompts and adhering to recommendations (Allen, Swift, Nield, Liley, & McKenzie, 2020; Horsham, Antrobus, Olsen, Ford, Abernethy, & Hacker, 2020). Many users may neglect to wear the device consistently, ignore alerts to reapply sunscreen, or fail to maintain the device in proper working condition, limiting the protective benefits. Furthermore, devices like the L’Oreal My UV Patch or the La Roche-Posay UV sensor require regular interaction with a smartphone app to receive full benefits, and users who do not engage with these apps may miss important updates on their exposure levels (Shi et al., 2018; Kurz et al., 2020). To maximize the protective potential of wearable UV devices, future designs may need to incorporate additional reminders or incentives that encourage regular use and interaction. Enhanced compliance-focused features could improve both short-term and long-term adherence to sun safety practices, contributing to reduced UV-induced skin damage.

Variability in device performance across different skin types is another critical challenge, as not all UV wearables are equally effective for every user. As the L’Oreal My UV Patch relies on colorimetric changes that may be less visible on darker skin tones, this potentially limits accessibility for individuals with higher Fitzpatrick skin types (Kurz et al., 2020). Additionally, wearable UV devices that account for skin sensitivity differences may not fully address the unique needs of all users, particularly those with atypical skin responses to UV radiation. This limitation underscores the need for further personalization in wearable UV technology to account for individual variations in UV sensitivity. Moreover, socioeconomic factors influence the accessibility and distribution of these devices. Many advanced UV wearables, while effective, can be cost-prohibitive, limiting access among users in underserved communities, as noted by Botti et al. (2023). This disparity suggests a need for public health initiatives, such as those recommended by Allen et al. (2020), to educate users about the importance of sun protection while also promoting the development of affordable options. Collectively, these limitations highlight the need for ongoing research to refine wearable UV technologies, ensuring they are accurate, durable, and accessible to a broader range of users.

2.8 Low-Cost, Accessible UV Protection Solutions

The development of affordable and accessible wearable UV sensors is crucial for expanding public access to sun safety tools, especially for individuals in underserved communities. Researchers have explored cost-effective materials, such as TiO_2-based hydrogels, to create colorimetric sensors that visually indicate UV exposure levels. Botti et al. (2023) developed a TiO_2 nanocomposite hydrogel that changes color in response to UV radiation. This material offers a simple and inexpensive way for users to monitor their UV exposure. Similarly, wearable UV indicators made from electrospun fibers embedded with photochromic dyes provide an intuitive color change as UV intensity increases (Zheng et al., 2020). Non-electronic devices offer an accessible approach to UV monitoring, enabling individuals to assess their exposure easily without relying on complex technology or mobile applications.

Other low-cost innovations harness biodegradable and environmentally friendly materials to develop UV sensors that are not only affordable but also sustainable. The use of nanocomposite films that are both flexible and translucent, provide reliable UV monitoring capabilities while remaining cost-effective to produce (Komatsu, Kawamoto, & Ikuno, 2022). Films can be incorporated into various types of wearable devices, including wristbands, patches, and even fabric-based sensors, making them adaptable for different use cases. The biodegradable nature of these materials allows for single-use or short-term applications, particularly in high-exposure settings where disposability and convenience are essential. Additionally, by utilizing eco-friendly materials, these devices minimize environmental impact, addressing growing concerns about electronic waste (Komatsu, Kawamoto, & Ikuno, 2022). This approach not only reduces production costs but also positions these sensors as a sustainable alternative to more complex electronic wearables, offering a practical solution for broader public access to sun safety tools. Such innovations align with the need for accessible UV protection solutions that cater to both individual health needs and environmental sustainability.

Advances in UV-responsive inks and printable materials have further expanded the accessibility of wearable UV sensors, as these technologies can be produced affordably and seamlessly integrated into everyday items. UV-sensitive inks that visibly change color upon UV exposure, allow them to be applied to textiles, wristbands, and even temporary tattoos (Kurz et al., 2020). Customizable, printable UV indicators offer a low-cost approach to UV monitoring, making sun protection tools accessible to a wider audience. Similarly, AlQahtani et al. (2022) explored solar bands equipped with integrated color sensors that not only measure UV exposure but also classify skin types to provide personalized sun safety feedback. These devices, which range from colorimetric sensors to multifunctional health monitors, play a significant role in promoting sun safety behaviors by providing real-time UV exposure feedback. Table 1 illustrates how device functionality, accessibility, and usability influence user engagement, especially in diverse outdoor settings. This innovation underscores the potential for low-cost, customizable solutions to deliver tailored protection recommendations, making advanced sun safety tools more accessible to individuals who may lack access to traditional wearable technology. By focusing on cost-effective and accessible solutions, tailored innovations help bridge gaps in sun safety resources, enabling broader access to UV monitoring technology. A strong emphasis on affordability and simplicity supports the public health goal of reducing skin cancer incidence by making UV protection more readily available and practical for diverse populations. Through groundbreaking advancements, wearable UV sensors can effectively promote sun safety awareness and encourage proactive sun protection across varied demographic groups.

Table 1 summarizes various wearable UV devices, highlighting key technologies, features, applications, limitations.

Table 1. Overview of Wearable UV Devices and Their Impact on User Engagement

Device	Key Technology	Features	Applications	Limitations	Target Audience	Sources
L'Oréal My UV Patch	Colorimetric sensors	Visual color change, Smartphone integration	Tracks daily UV exposure, Personalized recommendations	Limited accuracy with prolonged wear, Requires app for detailed info	General public, beauty enthusiasts	(Kurz et al., 2020)
La Roche-Posay My Skin Track UV	Photosensitive material	Visual indicator, Real-time UV tracking via app	Skin health tracking, Promotes sun safety behaviors	Dependent on smartphone, color change visibility varies with skin tone	General public, dermatology patients	(Shi et al., 2018)
SunFriend	UV LED sensors	Visual LED indicators for exposure levels	Tracks UV exposure, Enables sun safety awareness without smartphone	Limited sensitivity, No detailed UV readings	Outdoors enthusiasts, sensitive skin	(Esfahani, 2021)
Smartwatch	UV & Temperature sensors, Smartphone sync	Real-time monitoring, App alerts	Multifunctional health monitoring, Continuous data collection	High cost, Requires smartphone connectivity	General public, tech enthusiasts	(Alam et al., 2024)
UV Patch	Colorimetric sensors	Visual color change;	Daily UV exposure tracking,	Limited accuracy due to	General public,	(Kurz et al., 2020)

		Smartphone integration	Personalized feedback	environmental interference	festival-goers	
Wristband	Nanocomposite hydrogels, TENGs	Durable, flexible, self-powered	Continuous wear, ideal for high UV exposure areas	Recalibration needed, Environmental interference	Athletes, outdoor workers	(Botti et al., 2023; Chen et al., 2023; Chen et al., 2023; Chen et al., 2022)
Solar Band	Color sensors, Solar-powered	Skin type classification, Visual UV indicators	Sun safety, Suitable for environments with intense sun exposure	Limited to outdoor use, May need frequent exposure to direct sunlight	Drivers, outdoor enthusiasts	(AlQahtani et al., 2022)
Phototherapy-integrated Device	UV-A LED, Biochemical sensing	UV protection & treatment; Tracks Vitamin C	Medical, Phototherapy for skin conditions	Complex, high cost, Requires user compliance	Medical patients, dermatology clinics	(Song et al., 2023; Amador-Mendez et al., 2024)
UV-Responsive Inks	Printable materials	Customizable, color-change on textiles	Temporary use, Ideal for festivals and outdoor events	Non-reusable, Less accurate under mixed light conditions	General public, festival-goers	(Kurz et al., 2020)
Textile-integrated UV Indicators	Electrospun fibers with photochromic dyes	Visible color change in response to UV	Easy visual UV monitoring, Suitable for daily wear	Limited to color-change feedback, Less detailed information	General public, outdoor workers	(Zheng et al., 2020)

2.9 Future Research

While wearable UV devices have demonstrated significant potential in augmenting existing photoprotection strategies, there is a clear need for large-scale clinical validation studies to further refine their accuracy, reliability, and usability across diverse demographic groups. Studies should focus on addressing calibration drift, environmental interference, and user variability to ensure that these devices function consistently in real-world settings. Moreover, research must evaluate the effectiveness of these devices among individuals of different skin types and geographic locations, accounting for factors such as UV intensity and climate variability. By conducting large-scale trials, researchers can assess the long-term protective benefits of these wearables and identify any performance gaps that need to be addressed. Cross-disciplinary collaboration among technology developers, dermatologists, and public health experts will be essential in guiding these studies, ensuring that wearable UV devices are optimized for both technological precision and health impact. Such collaborations will provide a more comprehensive understanding of how wearable UV devices can best contribute to public health initiatives focused on reducing UV-induced skin damage.

Further research should also consider the socioeconomic disparities that impact access to wearable UV technology, as well as the need for public education to maximize user engagement and compliance. Efforts should be made to explore cost-effective materials and designs that make these devices more affordable and accessible to underserved populations. In parallel, public health initiatives could integrate educational programs that highlight the importance of consistent UV monitoring and sun protection behaviors. Enhanced integration with teledermatology and mobile health platforms presents an opportunity to expand the reach of these devices, providing personalized feedback and education on sun safety directly to users. Future advancements in AI and data analysis could enable wearable UV devices to offer more precise, adaptive recommendations by analyzing cumulative exposure data and adjusting based on real-time changes in environmental conditions. By addressing socioeconomic and educational barriers and advancing AI capabilities, future research and development can help ensure that wearable UV devices serve as effective tools for comprehensive sun protection, empowering individuals from all backgrounds to take proactive steps in protecting their skin health.

3. Conclusion

Wearable UV devices represent a transformative advancement in personalized UV protection, offering real-time monitoring, tailored feedback, and greater accessibility for diverse populations. Through innovations in material science, such as nanocomposites and flexible hydrogels, these devices have evolved to become more comfortable, durable, and adaptable for a range of environmental conditions. Self-sustaining power solutions, including bioinspired sensors and solar energy harvesting, further enhance their practicality and environmental sustainability. However, the potential of wearable UV sensors is not without limitations; issues such as calibration drift, environmental interference, and variability in effectiveness across skin types remain areas for improvement. Additionally, accessibility challenges, socioeconomic disparities, and the need for effective public education present significant barriers to their widespread adoption. Addressing these limitations will require large-scale clinical validation studies, cross-disciplinary collaboration, and targeted public health initiatives that prioritize affordability and inclusivity. By refining these technologies and integrating them with mobile health platforms and teledermatology, wearable UV devices can play a crucial role in comprehensive sun safety strategies, empowering users to take control of their UV exposure and reduce their risk of UV-induced skin damage. As this field advances, wearable UV technology has the potential to significantly impact public health efforts by promoting proactive sun protection behaviors, making sun safety tools more accessible, and ultimately contributing to the reduction of skin cancer incidence on a global scale.

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